Long-Path Propagation

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A STUDY OF
LONG-PATH PROPAGATION
IN SOLAR CYCLE 22

by

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March 1992

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WHISTLER RADIO SERVICES

SUMMARY

This article provides the details of a year-long study of long-path propagation from the northwest corner of the USA. In that time, April 1, 1991, to March 21, 1992, almost 1,700 long-path contacts were made on the 14 MHz CW band in the early morning hours.

The location used in the present study is unique for the study of long-path propagation as it proves possible to separate LP contacts into four groups of paths with increasing distance and complexity. First, there is the path to the antipodal area at Crozet Island in the south Atlantic. Second, there are those paths which continue through auroral zone latitudes in Antarctica to South Africa as well as Sri Lanka and India. Next, there are paths across the geomagnetic polar plateau to east Africa and into the Indian Ocean. Finally, there are extreme polar paths which cross Africa and the equatorial anomaly of the ionosphere to reach European regions.

The long-path contacts were analyzed by groups according to the level of geomagnetic disturbance and according to season, either spring/summer or fall/winter, when the sun was above or below the equator. The data show the time-distribution of long-path contacts and how their frequency of occurrence was affected by geomagnetic activity during months 55 to 67 in Solar Cycle 22. Following the results of the study, the discussion concludes with a summary of the types of disturbances which may affect long-path propagation and the possible presence of chordal hops on the various paths.

PREFACE

Long-path DXing is a human experience involving amateur radio operators more than half an earth apart. As such, it reveals aspects of human psychology, sociology, and the demographics of our hobby. But we are always aware that long-path DXing is controlled by solar radiation, whether through slow changes with the solar cycle or sporadic outbursts from solar flares or coronal holes.

This article is directed toward the physical aspects of long-path DXing but tries to give some recognition to the human sides as well. Being a physical scientist, however, I must plead guilty to being biased in the technical direction. Perhaps the next person who pursues this matter can make up for my shortcomings.

Guemes Island, WA
March 1992

ACKNOWLEDGEMENTS

Many people contributed, knowingly and unknowingly, to the successful completion of this study. Among the latter were hundreds of amateur operators over half an earth away who responded to my calls. Their assistance is gratefully acknowledged.

Others, equally distant, responded many times to my calls, and I want to thank them for their kindness and patience. Among that group are the following, from near to far: Jean, FT4WC; Al Smith, ZS1AAX; Stan Reeve, ZS5ADV; Eric Meyer, ZS6ME; Frank Franklin, Z21FN; Les Antrobus, 7Q7LA; Shanti Perara, 4S7WP; Niri Niranjan, VU2NI; Abid Solim, 3B8FG; Stanley Ingram, EA6ZY; Ed Kislyakov, UB4LCD; Petar Krajcev, YU5PK; Joerg Vollbrecht, DL2HQH; André Marcay, F2MA; Harry Vollema, PA0LVB.

In the analysis phase, I was most gratified to receive LP log data for sub-auroral paths in response to my request. Those generously contributing included Merle Parten, K6DC; Cliff Moore, K6KII; Rad Leonard, W6THN; and Ron Faulkner, W6TUR, from the USA, and Al Smith, ZS1AAX; Jack Snyman, ZS1OU; Jim Van Loggerenberg, ZS2LR; Bob Wilson, ZS2RW; Stan Reeve, ZS5ADV; Jay Gordon-Welsh, ZS6BUD; Eric Meyer, ZS6ME; Mac McDonald, ZS6UE; and Frank Franklin, Z21FN, from the continent of Africa.

I am indebted to Armond Noble, N6WR, for use of the logo of my propagation column in *Worldradio* and to Robin Wortley, KC6RUD, for so ably adapting it to long-path. And I am pleased to acknowledge the generous assistance of Sheldon Shallon, W6EL, for many discussions about HF propagation and related topics. Further, I wish to acknowledge the efforts of Evans Paschal, KF7VX, in laying out and typesetting the article. And finally, I wish to thank my wife, Mary Lou, NM7N, for her patience in the past year and for discussions about statistical methods in data analysis.

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But be ye doers of the word,
and not hearers only,
deceiving your own selves.
James 1:22

PART 1

1.1 Introduction

Aside from the inherent curiosity or mystery of "long-path," it has provided determined DXers on the West Coast with those rare Middle East zones that are so elusive working with just short-path propagation. Now if you're thinking about getting into "long-path," how much have you thought about how it really works and may vary within a year or even a solar cycle? I started worrying about those ideas a while back and finally decided to work it out as best I could, on the air and with my computer. So what follows is a saga, almost twelve months on the 20-meter CW band working nothing but "long-path" and with some computer exercises to match.

While doing that, I was collecting all the solar and geophysical data that NOAA and others had to offer; that would be needed to interpret the results. With the aid of my computer, working out regression analyses and various details such as distance, heading, and paths to DX stations, I think I've pulled together the various aspects of long-path propagation into a coherent whole. Thus, in what follows, I'll be summarizing my own experience as well as suggesting some guidelines for others to use in working with this fascinating mode.

In nearly twelve month's time, from April 1, 1991, to March 20, 1992, I made almost 1,700 long-path contacts on 20-meter CW with locations like Crozet Island, stations in the Indian Ocean area, South Africa, and beyond into Europe. Indeed, in contacting places as close as Crozet Island (20,465 km) and as far as Vadsö, Norway (33,368 km), the total distance my RF travelled in those contacts was at least 46,000,000 km. Now that's about the same as 1,150 trips around the earth or 60 round-trips to the moon!

In carrying out this project, I was up early, day after day, and "running radio" for about three hours starting around 1200–1400 UTC in the morning, depending on the season. If the previous day's propagation forecast suggested that conditions might be disturbed, I copied both the Solar and Propagation Bulletins from the NOAA BBS before going on the band. In any event, I always checked the latest Boulder K index by monitoring WWV or WWVH broadcasts.

For some people that might seem like a form of self-punishment, but I'm a "morning person." Besides, I was really curious about the fundamental aspects of long-path, and, as you already know, one can't find any decent literature on the subject. I say that as what I did find in handbooks and antenna books amounted to two things: 1) long-path DXing involved pointing one's beam opposite to the normal direction (that's little more than a definition), and 2) something about the gray line and sending one's signals in its vicinity (that's a bit more than a definition but hardly what I'd call an in-depth discussion in terms of ionospheric physics). I knew there had to be more to long-path propagation than that so I went to work, trying to develop information in a more organized fashion.

Now I've spent a lot of time at this, enjoying (?) every moment, and, being an open person, I want to share the results with you. So sit down and read on but be prepared for a lengthy discussion. After all, it took over 1,000 hours on the air to carry out this study; that's more than twenty-five 40-hour work-weeks so you can't expect me to put it down on paper in 1,000 words or less! That's for school-boy compositions; this is serious business, propagation and DXing on long-path!

1.2 Basic Parameters of the Study

Maybe you didn't notice it but I called this effort a "study." I use that term advisedly as it was not a controlled experiment. I've conducted my share of those during my academic career. This was a study run by one amateur radio operator, with the help of many hundreds of amateur radio operators more than half an earth away, and was meant to deal with the experience we call long-path DXing. But it has its technical aspects as well. I will try to go through them in an orderly fashion as we get into the matter.

So, first, I have to stake out the basic parameters of the study. Thus in making LP contacts I used a Ten-Tec Corsair as my transceiver, a linear amplifier running about 200–250 watts output, and a generic 3-element tri-band Yagi antenna at 38 ft above ground. All that amounts to a mid-scale DXer's set-up. But my QTH is a bit different in that it is located on an island, truly a low-noise site; in addition, it is perched on a bluff, overlooking the Guemes Channel north of Anacortes and with my tri-bander looking south at about 75 ft above salt water.

As for operating, I was on the band promptly every morning, patrolling the first 50 kHz of the 20-meter CW band, logging the band conditions, long-path signals that I heard, and contacting as many as I could. Thus I responded to CQ's, "QRZ?," or "tail-ended" QSO's, but never tried calling CQ, CQ DX or CQ LP. I generally spurned pile-ups but did create some from time to time by getting lucky, right at the head of the line. That's one advantage to being on the band constantly; you get to know when a fist sounds new or an operating style is different.

1.3 First Results

To get started, let's outline the boundaries of this study and then give some of the results. For example, of the 355 days in the study I was active and looking for contacts on 339 days. The difference between those two numbers is due to the fact that I simply did not pursue any long-path (LP) contacts on 16 days during major amateur radio sporting events (Field Day, Sweepstakes, CQ or ARRL DX Contests, and the like from abroad).

So now we come to the first and simplest result of the LP test: in those 339 days I had at least one LP contact on 312 days. And by an LP contact I mean one that covered more than half the distance around the earth and involved a least the minimum exchange of call, RST and QTH. So there you have it, on 92% of the days of the period LP was open from this QTH. The remaining 27 days were unproductive on LP because of solar or geomagnetic disturbances. And I'll have more to say on those points later.

Now if you look at the whole study, the average number of LP contacts per active day amounted to 5.0 so the LP statistics are not on the puny side. Indeed, LP was open on almost all the days without major geomagnetic storms and produced not just isolated contacts on this day and that but, instead, a significant number of contacts each day, anywhere from one to twelve. And, of course, for the DXers who are impatiently reading this, LP also gave rise to some new prefixes in the log, say 3A2, 3B7, 3B9, 5R, A2, A4, A9, C9, D2, FH, FR5/T, J2, S21, V51, and even ZA1. So I've many more pins on my DX map now, thanks to LP propagation!

But I digress. The point I'm trying to make is that the overall features of the study show that LP propagation was a basic feature of the undisturbed ionosphere, one that was supported regularly without the need to invoke any unusual or exotic circumstances for explanation. In short, it was there almost all the time in that period so all one had to do was be "on the air" at the right time, early in the morning here on the West Coast, to make LP contacts with Crozet Island, Africa, and beyond, ... way beyond!

Further, high power or big antennas were not always required at the other end, as I worked my share of stations who ran 100 watts into dipoles, inverted vees, slopers, and verticals, to say nothing of Janusz, ZS5ADU/M, who drove around Durban, South Africa, with 80 watts into a mobile whip.

But there were differences with seasons of the year and levels of geomagnetic activity. While the seasonal effects were gradual, the changes were not small nor subtle, being quite evident when you look at the times when LP DX was coming in and the prefixes heard on the band. Geomagnetic activity, however, was sporadic in time, varied markedly in degree, and had an effect on the ionospheric conditions.

The main change with seasons was that stations in the Indian Ocean area, say in Sri Lanka and India, were no longer heard when the southern hemisphere went into its summer season. That was the result of increasing ionospheric absorption as their long-paths to this QTH became more illuminated. Thus paths which went off into the east from here, toward the sunlit hemisphere, soon became ineffective as the summer season progressed in the southern hemisphere.

But that same shift of the sub-solar point resulted in the winter season in the northern hemisphere and had another effect on LP signals which went to the west from this QTH. In particular, for signals to and from Europe, the shift in seasons actually reduced the illumination on the portions of the paths over Europe; the result being that more of Europe was open, and those contacts on LP became much more frequent.

All in all, the loss of the signals from the Indian Ocean area as well as the appearance of more European

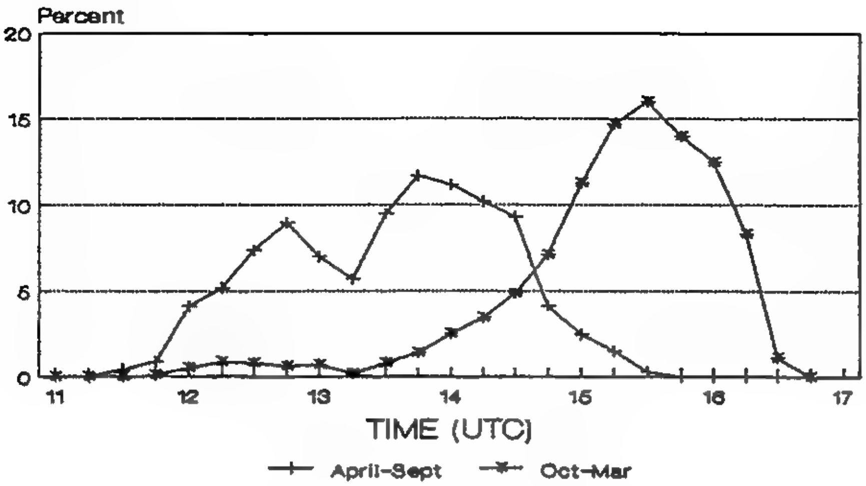


FIGURE 1. Time-distribution of long-path contacts by season.

signals had the effect of shifting the time-distribution of LP contacts toward later hours. This result was quite striking, as seen in Figure 1 where the time-distribution of contacts for the two seasons is displayed in 15-minute intervals. That shift also involved a change in the calls contacted, from those in eastern Europe to those in western Europe. Part of that is sociological in origin, having to do with the change in time of the end of a work day.

Since that shift resulted from processes in the lower regions of the ionosphere as solar illumination changed, it requires little more in the way of explanation. But that is not the case for other aspects of LP propagation, involving ionization in the F region as well as where the paths travel with respect to the geomagnetic pole. Those aspects are a bit more complicated, especially when it comes to solar and geomagnetic disturbances, and will be dealt with in the next sections.

1.4 Solar-Terrestrial Conditions

Maybe you didn't notice it but there was an important phrase, "in that period," in one of the previous paragraphs. Thus one must not forget just when this study was carried out, from month 55 to month 67 of Solar Cycle 22. And it included a good measure of solar-terrestrial disturbances which disrupted the amateur bands and the DX study as well, June, July, and October '91 being cases in point. Later I'll go through a list of those events in some detail, commenting on how they affected LP propagation.

Treating simple things first, we've become accustomed to following solar cycles in amateur publications by noting the monthly sunspot numbers R_i reported by the Observatoire Royal de Belgique. Those values are converted to 13-month smoothed values, and for the period of the present study that number was around 146 and declining from an earlier peak value of 158 in July '89.

Here in the USA, a measure of magnetic activity is often obtained by noting the daily estimates of the Boulder A index given during WWV broadcasts, increases in that index usually being associated with ionospheric disturbances. For the period of the study, the Boulder A index ranged from a low of 2 to a high of 150.

Those same broadcasts from WWV also announce solar flares as well as the proton events observed by NOAA's GOES satellite and polar cap absorption (PCA) events observed at Thule, Greenland. Those events are a bit more involved since their occurrence affects propagation in several different ways — sudden ionospheric disturbances from flare X rays, delayed magnetic storms, or fairly prompt absorption of HF signals going across the polar caps.

Not every flare results in all those effects so the date and time of occurrence of large flares is given on WWV as an advisory or warning to those using HF radio communication. Those requiring more detailed information about solar activity and propagation forecasts obtain it from the NOAA/SESC BBS. For example, forecasts

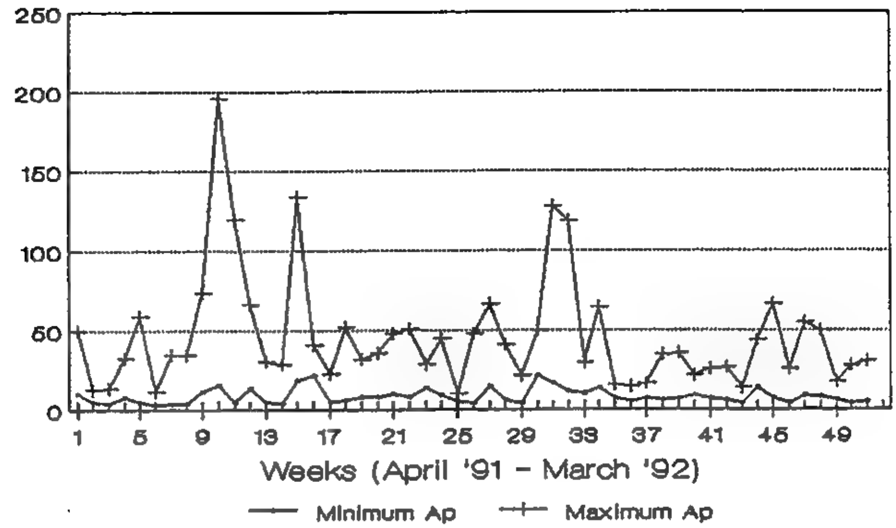


FIGURE 2. Weekly maxima and minima of the *Ap* index, April 1, 1991, to March 20, 1992.

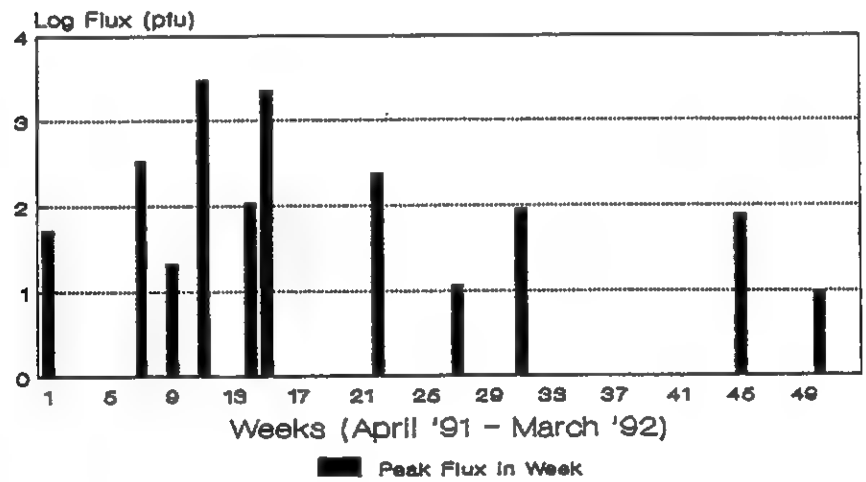


FIGURE 3. Weekly peak flux of solar protons above 10 MeV observed on the GOES satellite, April 1, 1991, to March 20, 1992.

are given for the magnetic index *Ap* as well as future activity of regions on the solar disk.

The occurrence of magnetic storms is particularly disruptive for radio propagation, and the past year had its share of them. This is shown in Figure 2 where weekly values of *Ap*, both maxima and minima, are given. Here it should be noted that minor storm conditions are present when *Ap* is between 31 and 50 while major storm conditions are when *Ap* exceeds 50.

As for the solar proton events, the announcements on WWV are based on detailed observations. In particular, detectors on the GOES satellite are set to monitor the fluxes of solar protons in various energy ranges. For broadcast purposes, however, the units used in reporting the events are simplified to *proton flux units* or pfu in each energy range and a *satellite proton event* is announced if the flux of solar protons with energies greater than 10 MeV exceeds 10 pfu.

Particles of that energy can penetrate to an altitude of 65 km in the polar regions, spiraling down the magnetic field lines. When that happens, additional ionization is created in the *D* region, but the actual amount of ionospheric absorption depends on details of the proton energy spectra as well as the amount of

sunlight on the region. For example, the first PCA event in this study was a modest one and occurred on April 3, 1991, the proton flux reaching 52 pfu and giving rise to 2.2 dB of absorption for 30 MHz signals from the vertical direction at Thule, Greenland.

There were a total of 14 proton events in the course of this study, and the peak flux recorded during each week is shown in Figure 3. The association of those flare events with magnetic disturbances may be noted by comparing the proton peaks in Figure 3 with the peak values of *Ap* in Figure 2. And finally, the magnitude or importance of PCA events to HF propagation may be appreciated by the fact that the event of June 11, 1991, with a flux of 3,000 pfu, resulted in about 17 dB absorption on 30 MHz for a single, vertical traversal of the ionosphere at Thule, Greenland.

1.5 Long-Path Propagation and Magnetic Disturbance

With that background, we can look at the overall effect of magnetic disturbances on the LP study by examining the data in Table 1. This shows the number of active days in the study according to the range of the planetary magnetic index *Ap*, say the number of days when *Ap* was between 0 and 10, 11 and 20, 21 and 30, etc. In doing that we should note that major storm conditions exist when *Ap* exceeds 50, minor storm conditions for *Ap* between 31 and 50 and non-storm conditions when *Ap* is 30 or less.

And to look at things in a bit more detail, let's note how many sessions yielded not a single LP contact, how many involved just one LP contact, and how many there were with more than one LP contact. This information is shown in Table 1.

TABLE 1. Total Sessions and Sessions by Number of Contacts vs. *Ap* Index.

Ap Index	Days	Contacts/Session		
		0	1	> 1
0–10	98	0	6	92
11–20	96	2	3	91
21–30	62	1	6	55
31–40	28	3	3	22
41–50	15	1	3	11
51–60	14	5	2	7
> 60	26	15	3	8

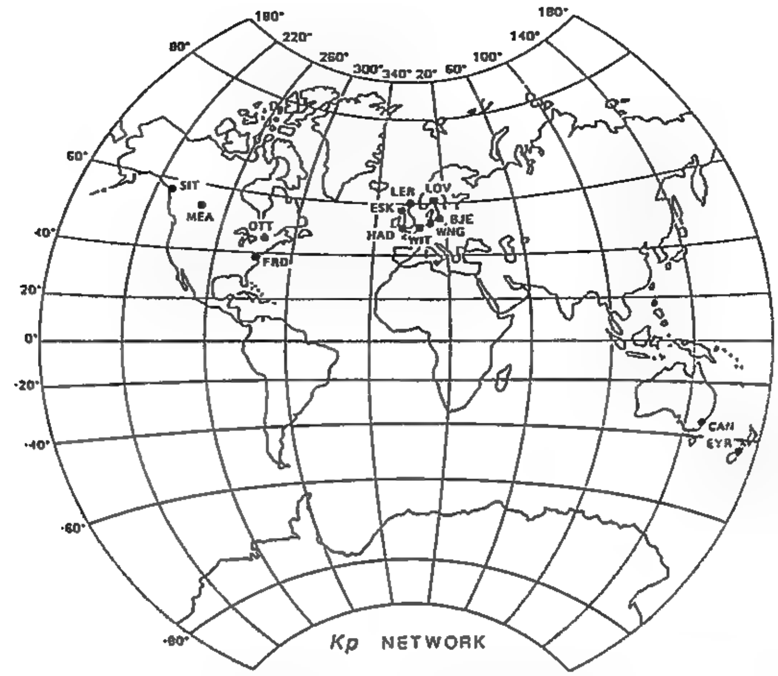
Of the 339 days there were 256 days of non-storm conditions, and on 3 of those days no LP contacts were made, on 15 days only one LP contact, and 238 days involved more than one LP contact. On that basis, at least one LP contact was made on 253 of the 256 days, or 99% of the non-storm days!

Similarly, of the 43 days with minor storm conditions, at least one LP contact was made on 39 days, or 91% of the minor storm time; and for the 40 days of major storm conditions, at least one contact was made on 20 days, or 50% of the major storm time. The last point is rather amazing when you consider the havoc that storm conditions wreak on the HF bands.

It should be pointed out that the planetary index *Ap* used in Table 1 has a broader basis than the *A* index given during WWV broadcasts; those values are based only on magnetometer data recorded at NOAA in Boulder, Colorado. The planetary index *Ap* was designed to measure solar particle radiation by its magnetic effects and has widespread acceptance in the US and western Europe as a means of characterizing the level of geomagnetic activity. It is prepared monthly by the International Association of Geomagnetism and Aeronomy (IAGA) at the Institute for Geophysics, Gottingen University, Germany.

As noted earlier, the maximum and minimum values of *Ap* for each of the weeks in the study are shown in Figure 2. These were obtained from monthly reports of *Ap* which summarize data from 13 observatories between 44° and 60° northern or southern geomagnetic latitude. In the north, 11 of the observatories lie in a band of 179° geomagnetic longitude in extent, from Sitka, Alaska (60° N, 275° E), eastward to Wingst, Germany (54° N, 94° E); and in the south the two observatories are located at Eyrewell, New Zealand, and Canberra, Australia, as shown in Figure 4.

An estimate of the *Ap* index is released daily on the NOAA BBS by the Space Environment Services Center (SESC) in Boulder and is based on data from five magnetic observatories in the northern hemisphere,



Northern Hemisphere Observatory	Code	Corrected Geomag. Latitude
Meanook	MEA	62.5°
Sitka	SIT	60.0°
Lerwick	LER	58.9°
Ottawa	OTT	58.9°
Lovö	LOV	56.5°
Eskdalemuir	ESK	54.3°
Brorfelde	BJE	52.7°
Fredericksburg	FRD	51.8°
Wingst	WNG	50.9°
Witteveen	WIT	50.2°
Hartland	HAD	50.0°

Southern Hemisphere Observatory	Code	Corrected Geomag. Latitude
Eyrewell	EYR	50.2°
Canberra	CAN	45.2°

FIGURE 4. Magnetometer sites in the *Ap* network in 1988. From *Menvielle and Berthelier* [1991].

extending over 187° in geomagnetic longitude from College, Alaska, eastward to Upper Heyford, England. Lacking observations from the southern hemisphere, there are bound to be differences between the daily estimates of *Ap* and the values of *Ap* from IAGA.

An analysis of three years of data indicate that the correlation coefficient between the estimated *Ap* and *Ap* itself is 0.91; however, given the fact that the geomagnetic field is quiet far more often than disturbed, the differences between the two are most evident during disturbed times. Even at that, however, the availability of an estimate for *Ap* proves to be invaluable.

Returning to Table 1, it should be noted that, since it includes all the active days of the study period, it follows that the overall features of Table 1 give the distribution of the *Ap* index during the study. Thus it is seen that a total of 76% of the LP sessions were during days with non-storm conditions, when *Ap* was between 0 and 30, while 13% of the sessions were during minor storm conditions, when *Ap* was between 31 and 50, and the remaining 11% during major magnetic storm conditions, with *Ap* greater than 50. Later in this report the level of magnetic activity during the year-long study will be placed in perspective by comparing it with activity in the two years that preceded it.

Now going back to the other "numbers" for the time of the study, it covered a period when the smoothed sunspot number (SSN) was between 125 and 150. More to the point, however, was the daily average of

the 1–8 Å background X ray flux. That varied by a factor of about four, from 6.0×10^{-7} W m^{-2} to 2.4×10^{-6} W m^{-2}, over the entire period.

The second set of numbers are more related to the level of ionization that controls the refraction of the 14 MHz radio waves in the LP study. In contrast, the first numbers lead us to archival descriptions of the ionosphere in terms of f_oF_2 maps. And the 10 cm solar flux has been ignored as it is largely irrelevant in analyzing the results of the study, the archival aspect having been taken care of by the sunspot numbers.

But to go on, the LP data has been analyzed in more detail, according to seasons, great-circle paths expressed in geomagnetic coordinates, the "equatorial anomaly" of the ionosphere, and even the venerable gray line.

While Table 1 summarizes the results for the entire study, the same approach could be used for the two ionospheric seasons, spring/summer when the sun was above the geographic equator and the fall/winter season when it was below. This division of the data is important since it would show not only how geomagnetic activity differed in the two seasons but also bears on the amount of sunlight on the propagation paths during the study. Since the largest portions of the paths were in the southern hemisphere, the separation is particularly important.

But that last point touches on a problem which arises in using the Ap network in analyzing the LP observations. Thus there is only a limited range of longitudes in the southern hemisphere, near New Zealand and Australia, where geomagnetic data is sampled in preparing the monthly Ap reports. A better network exists, even providing more uniform coverage of both hemispheres. but before getting to it, we have some other items that require more discussion.

PART 2

2.1 Some Details of the Study

In dealing with LP propagation it is necessary to discuss details of the great-circle paths, some solar astronomy, and invoke properties of ionospheric charts, those critical frequency maps for f_oF_2 from days of yore. Let's take the matter of the great-circle paths first, followed then by solar astronomy. After that, more on geomagnetic indices is called for, and finally the bearing of f_oF_2 maps on LP propagation will conclude the discussion of experimental factors.

To begin, note that, at this QTH (48.5° N, 122.6° W) in the northwest corner of Washington, one looks southward to work LP into Africa and beyond. For the time period mentioned, about 1200 to 1500 UTC, contacts were made with 4S7's, VU2's and 3B9's in the spring/summer season by pointing the beam somewhat east of south toward the sunlit hemisphere. The rest of that southerly region, from Mauritius (3B8) to Capetown (ZS1), was contacted by pointing the beam west of south toward the dark hemisphere. It should be noted that there are seasonal effects here, especially for the 4S7's, VU2's and the 3B8's; those will be discussed later.

For those areas where amateur operators are most active, say in the African region as well as off into the Indian Ocean and toward South Asia, one can calculate the beam headings and distances, all in excess of 20,000 km, for each DX site. One can even calculate details of the great-circle paths to the locations, including the distance of closest approach to the southern geographic and geomagnetic poles.

As the seasons change, illumination along the paths will change also, affecting signal strength. That's a slow, steady process, but HF propagation can be disrupted suddenly, often without warning, by disturbances of solar origin. Thus there is also the question as to whether signals following those great circle paths could get into harm's way as they go into the far reaches of the southern hemisphere.

The experienced DXer knows the evils of which I speak: magnetic storms, auroral absorption (AA), and polar cap absorption events. They take their toll on HF signals without regard to hemisphere but not always equally. So the next task is to explore those possibilities as well, finding how close the great-circle paths come to the south magnetic pole (78.98° S, 109.1° E) [*Fraser-Smith*, 1987] before turning northward again toward Africa, the Indian Ocean, or Europe.

For this discussion, paths were categorized as being sub-auroral in latitude, in the auroral zone, or into the polar plateau, according to their maximum southerly excursion. The dividing lines are taken as below 60°southern geomagnetic latitude for sub-auroral (Sub-AZ) paths, from 60 to 70° for auroral zone (AZ) paths, and finally from 70 to 90° southern geomagnetic latitude for (Polar) paths into the geomagnetic polar plateau. That is a natural separation for the paths as auroral absorption events occur largely in the 60–70° range and polar cap absorption events affect HF propagation paths which go across the polar plateau.

2.2 Antipodal Considerations

I should proceed by presenting more of the results, but I must digress to make an interesting point. In particular, great-circle paths are the locus of intersections of planes which pass through the center of the earth. For a particular point of reference, say my QTH at 48.5° N, 122.6° W here in NW Washington, all great-circles that pass through it also pass through its antipodal point located diametrically opposite to my QTH at 48.5° S, 57.4° E. Indeed, one can think of all the great-circles through my QTH, no matter what their heading, as having a common diameter on the line joining my QTH and its antipodal point.

So what's so special about antipodal points? Well Crozet Island (FT4W) is close to being antipodal to my QTH! It's coordinates are 46.4° S, 51.9° E, only 465 km from my antipodal point. In essence, all the great-circle paths from my QTH pass close to that location. Let's put it another way around, Crozet Island

is close to being along all the paths *toward* my QTH for signals from all the other stations in the long-path directions I'm interested in!

That put Crozet Island in a special category, but another reason was the near-constant activity of Jean, FT4WC, during the spring/summer season. In The DX Bulletin, he was listed as one of the "Resident Amateurs on Regularly," and being near the focus of the paths to my QTH, he served as a beacon for me. But more important, it has been suggested that antipodal focusing is involved in LP contacts so contacts with Crozet Island were examined in the same manner as other contacts over larger areas, say Africa, the Indian Ocean, and Europe.

2.3 Some Great-Circle Paths

Enough talk; let's look at some numbers in Tables 2 and 3 which give particulars, say beam headings and distances, for some individual paths in the study.

TABLE 2. Auroral Zone and Sub-Auroral Zone Great-Circle Paths.

	Location	Heading	Distance	Maximum Latitude		Class
				Geog.	Geomag.	
ZS1	Capetown	258° E	23,590 km	49.6° S	58.8° S	S-AZ
ZS2	Port Elizabeth	250° E	23,070 km	51.4° S	61.4° S	AZ
V51	Namibia	245° E	24,570 km	52.9° S	63.3° S	AZ
ZS4	Bloemfontein	243° E	23,410 km	54.0° S	64.3° S	AZ
FT4W	Crozet Is.	238° E	20,465 km	55.9° S	66.7° S	AZ
4S7	Sri Lanka	154° E	26,550 km	72.6° S	67.4° S	AZ
D2	Angola	238° E	26,030 km	55.6° S	66.5° S	AZ
ZS5	Durban	237° E	23,050 km	56.2° S	66.8° S	AZ
A2	Botswana	238° E	23,800 km	55.9° S	66.8° S	AZ
ZS6	Johannesburg	236° E	23,540 km	56.4° S	67.4° S	AZ
VU2	Bangalore	158° E	27,120 km	75.6° S	68.6° S	AZ
3D	Swaziland	232° E	23,350 km	58.3° S	69.4° S	AZ

TABLE 3. Polar Great-Circle Paths.

	Location	Heading	Distance	Maximum Latitude		Class
				Geog.	Geomag.	
9J2	Zambia	226° E	24,530 km	61.6° S	72.8° S	Polar
Z2	Zimbabwe	224° E	24,160 km	62.5° S	73.5° S	Polar
3B9	Rodriguez Is.	168° E	23,240 km	82.3° S	74.9° S	Polar
7Q7	Malawi	217° E	24,160 km	66.3° S	77.3° S	Polar
3B7	St. Brandon Is.	176° E	23,550 km	86.2° S	78.4° S	Polar
3B8	Mauritius	180° E	23,130 km	89.7° S	81.0° S	Polar
5Z4	Kenya	206° E	25,610 km	72.9° S	82.7° S	Polar
FR	Reunion Is.	184° E	23,650 km	87.6° S	83.2° S	Polar
FR/T	Tromelin Is.	185° E	23,630 km	85.3° S	83.6° S	Polar
HZ	Saudi Arabia	189° E	28,340 km	84.4° S	85.1° S	Polar
5R	Madagascar	199° E	23,400 km	77.8° S	85.4° S	Polar
FH	Mayotte Is.	200° E	24,100 km	76.9° S	86.1° S	Polar

Table 2 contains a list of stations with paths from here which pass through the auroral zone, the only exception being Capetown which is barely in the sub-auroral category. And Table 3 contains a list of stations whose paths go across the polar plateau. Details of the long-paths may be seen by using the azimuthal equidistant map in Figure 5. Just follow a straight line southward from my QTH in the center of the figure on the beam headings given above. When the path is completed from the top of the map you can see which oceans and land masses were involved.

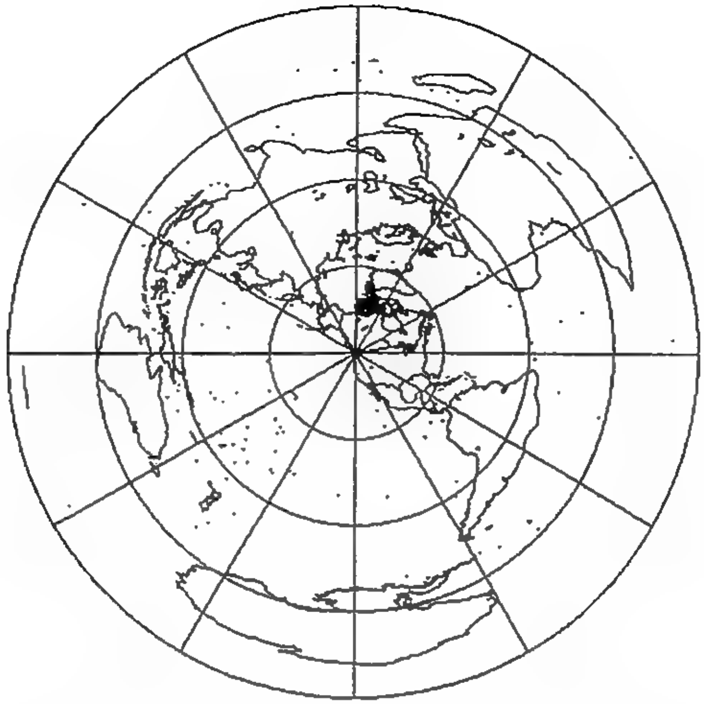


FIGURE 5. Azimuthal equidistant map centered on 48.5° N, 122.6° W.

In a more general sense, the azimuthal equidistant map in Figure 5 can be used to distinguish between the categories of paths. Thus, for this QTH, great-circle paths which go across the polar plateau are found at headings between 158° and 321° east of north. For paths which lie within the southern auroral zone, they are included between 135° and 158°, to the east of south, and between 231° and 254°, now west of south. Finally, paths with headings less than 135° or more than 254° fall in the sub-auroral zone category.

Now, if you like to have numbers to toss around, the average path length to the stations in Table 2 is about 24,100 km, and the average geomagnetic latitude of the most southern part of their great-circles is 65.6°. For the stations in Table 3, the average path length is not very different, about 24,300 km, but the southern reach of their great-circle paths is much greater, now 80.3°. So there you have it, the LP paths for the stations frequently encountered, especially in the first half of the study.

But there were other contacts, more distant than the 28,000 km to Saudi Arabia and ending well above the equator, during the second half of the study. Thus there was another important category, extreme long-paths or ELP, and those great-circle paths went across the polar plateau and Africa into the USSR, the Mediterranean, and western Europe. Its importance can be seen from the fact that extreme long-path contacts in the study outnumbered all the LP contacts to the locations given in Tables 2 and 3 by at least a factor of 2.

2.4 And Some Solar Astronomy

We all know the sun creates the ionosphere, and there are seasons for it as well as for the neutral atmosphere, depending on the whether the sub-solar point is above or below the equator. In presenting the results of the LP study, I will consider only two seasonal divisions, spring/summer for one and fall/winter for the other, and these have bearing on regions of ionospheric absorption in the D region as well as the details of the critical frequency maps for f_oF_2. To proceed, let's start with the gray line, a region of twilight along the terminator.

For discussions of LP, the gray line has enjoyed a prominent role, and one can explore that in detail using the GEOCLOCK program or, more simply, by using the plastic slides of The DX Edge. For purposes of illustration, Figures 6 and 7 were prepared from The DX Edge using the months of June and December,

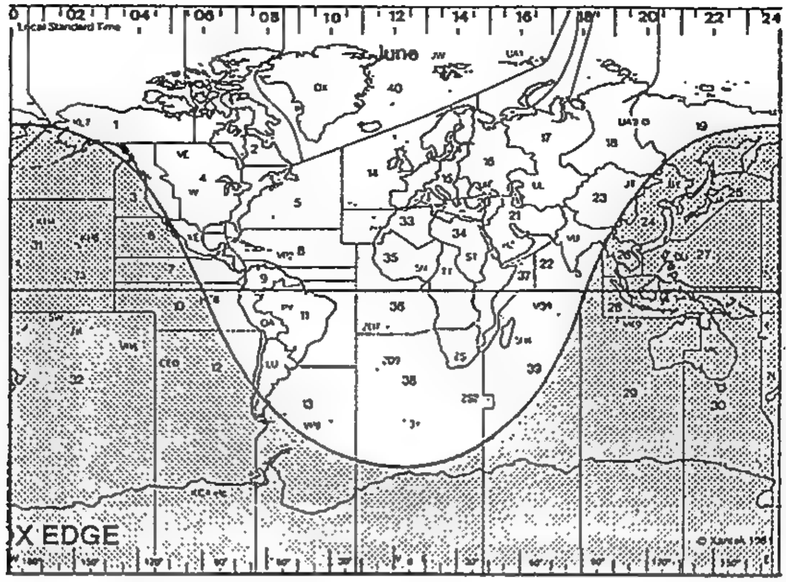


FIGURE 6. The DX Edge setting for approximately 1230 UTC during June.

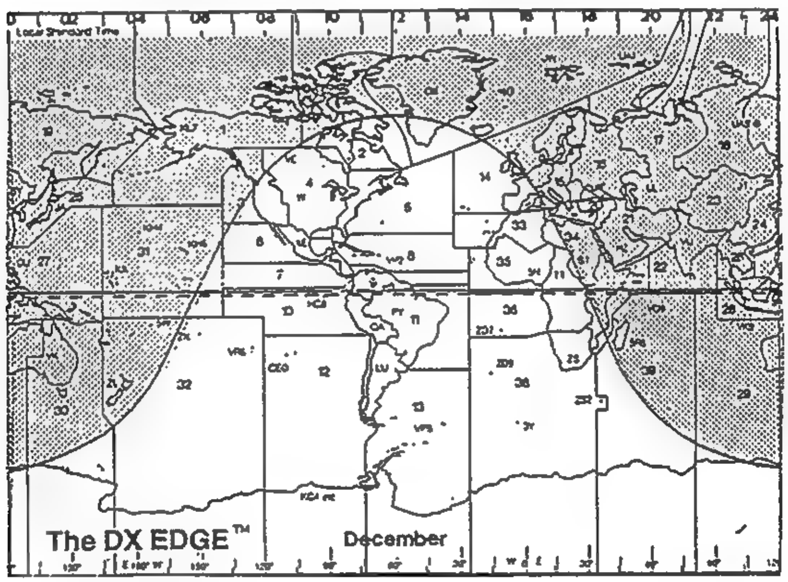


FIGURE 7. The DX Edge setting for approximately 1530 UTC during December.

respectively, and the times chosen for when the mean monthly terminator or gray line passed close to my QTH.

From Figure 6 it is apparent that paths to India and Sri Lanka are close to the gray line around 1230 UTC in June, and it is not surprising that during the early months of the LP study both 4S7's and VU2's were contacted regularly at the outset of an LP session. Those contacts were consistent with what might be called "conventional wisdom," the path being sheltered from solar illumination by its location in the twilight along the gray line.

Having cited those circumstances, now let me take the contrary position, perhaps in the extreme, that gray line considerations play only a limited role in LP propagation. Here, I go to June 6, 1991, when I

contacted VU2JOS in India at 1249 UTC; that was at a heading of about 160° east, at a distance of about 27,000 km and 202° eastward in longitude from my QTH. But about 80 minutes later, at 1407 UTC, I contacted D2ACA in Angola; that was at a heading of about 240° east, at a distance of about 26,000 km and 224° westward in longitude from my QTH.

In the first instance my signals were passing over the southern tip of Argentina, like on other occasions when I've heard VU2's and 4S7's in QSO's with LU8X's on Tierra del Fuego. In the second instance my signals were going off toward Tasmania (VK7) and almost at right angles to the direction for the gray line. Indeed, the contact with D2ACA was accomplished by brute force (in more ways than one!) and had absolutely nothing to do with going along the gray line!

Don't take the last remark to suggest that I fail to appreciate the value of the gray line. It's just that there's much more to LP propagation than such narrow or limited use of *D* region considerations, important as they are for DXing. Indeed, to make the point by using the weight of numbers, let me say that, between the first and last contact with a 4S7 or VU in the spring/summer season when the gray line was in their favor, I had more than 200 solid contacts with stations on the African continent, all with beam headings some 60–80° away from the gray line and into the dark hemisphere off to the west. Enough said!

2.5 Seasonal Features of Long-Path Propagation

Earlier, mention was made of the various disturbances during the period of the LP study. Going back to Figures 2 and 3, one notes that the first half of the study period was much more disturbed than the second half. That alone might make it reasonable to divide the study into two portions. But. as indicated earlier, there is a better reason in the fact that there are really two ionospheric seasons which are distinguished by whether the sub-solar point is above or below the earth's equator, the spring/summer and the fall/winter.

That being the case, we should go back to Table 1 and divide the entries according to those two seasons. That is done in Table 4.

TABLE 4. Total Sessions and Number of Contacts vs. *Ap* Index, Separated by Season.

Ap Index	Spring/Summer Days	LP QSO/Session			Fall/Winter Days	LP QSO/Session		
		0	1	> 1		0	1	> 1
0–10	51	0	6	45	47	0	0	47
11–20	39	2	2	35	57	0	1	56
21–30	31	1	5	25	31	0	1	30
31–40	16	2	1	13	12	1	2	9
41–50	10	0	3	7	5	1	0	4
51–60	7	4	0	3	7	1	2	4
> 60	14	7	2	5	12	8	1	3

There were 168 active days in the spring/summer season and 171 in the fall/winter season. Of the two ionospheric seasons, non-storm days accounted for 72% of the spring/summer season and 79% of the fall/winter season. By the same token, days with minor and major storm activity accounted for 28% in the first instance and 21% in the second. To a certain extent, these features are borne out in the contact data, suggesting a negative correlation between LP propagation and magnetic activity. However, this matter is better examined using the various paths in the study.

But to return to gray line considerations, their importance can be found in the case of the annual coming and going of some LP signals. For example, at my QTH that is the case for the 4S7's and the VU2's as their locations are north of the geographic equator. As a result, even from this high latitude those great-circle paths are fairly shallow and only reach 73–75° S geographic latitude. Thus, after the summer solstice, the terminator moves southward from its position shown in Figure 6, and the great-circle paths favored earlier by darkness eventually become illuminated, with signals gradually consumed by *D* region absorption after the autumnal equinox.

So the last contacts with Sri Lanka or India were around October 6, and no signals were heard from those regions after October 12. However, the signals did come back again the next year, just like the first swallows

of spring, with signals heard again after Valentine's Day and contacts made in the last week of February as the terminator started to move north again.

The case for 4S7's and VU2's is obvious, "by inspection" as is sometimes said, but it is less clear for stations in the Indian Ocean area that lie below the geographic equator. For them, one turns to the seasonal changes that take place in the heading of the sunrise portion of the terminator. At this QTH, the sunrise heading swings from 143° east at the summer solstice (see Figure 6) and reaches 217° east at the winter solstice (see Figure 7); then it swings eastward again, finally reaching 143° east at the next summer solstice.

As long as the great-circle heading to a DX station is west of the heading of the sunrise terminator, the path may be in darkness for a significant amount of time in the morning hours, making LP contacts possible with the DX QTH. But when the heading of the sunrise terminator swings past the great-circle heading to the DX station, the time the path is in darkness decreases rapidly, and finally it becomes fully illuminated, making LP contacts increasingly difficult at the usual time of day due to *D* region absorption.

The last discussion brings up another point which warrants mention, the fact that the loss of LP propagation from this high latitude is one thing but can be something quite different at lower latitudes along the West Coast. Indeed, the difference in LP propagation depends on the mechanism. For example, with Los Angeles (34.0° N, 118.25° W) as an origin, great-circle calculations for paths to Sri Lanka and India show the paths reach 69–72° south geographic latitude. On that basis, gray line considerations would show that LP signals from Sri Lanka to Los Angeles would be lost somewhat earlier than at this latitude.

2.6 More on Geomagnetic Indices

There are other mechanisms which may result in LP loss, not regular and orderly as the one from the seasonal motion of the terminator across the ionosphere but from solar outbursts, say geomagnetic storms, auroral absorption, and polar cap absorption events. For that discussion, we need to analyze the results of the study using the paths given earlier in terms of geomagnetic coordinates, finding whether they pass through the auroral zone or not, cross the polar plateau, or represent cases of extreme long-path, as mentioned earlier. Moreover, these disruptions of LP propagation are related, one way or another, to disturbances of the geomagnetic field. Thus we need to review the question of geomagnetic indices to be sure that what is used can be considered adequate for the discussion.

But before doing that, it should be noted that the contacts made on the different types of paths also involve three distinct population groups in the amateur radio community. The auroral zone group involved amateur operators from southern Africa, the current amateur radio census showing their total number to be about 6,500. The extreme long-path group reside in the USSR and Europe, numbering in excess of 100,000, while the polar group come largely from islands in the Indian Ocean and number less than 500. As a result, one should focus on how magnetic activity affected contacts with members of a given group and not try to make comparisons between groups or paths involving disparate populations.

In approaching those questions, it is important to note that there is a question about the adequacy of the *Ap* network. The problem is that the *Ap* network, established in 1939, covers only part of the northern hemisphere and seven of the observatories in the northern hemisphere are located in western Europe. Moreover, the coverage in the southern hemisphere is limited to the small region around New Zealand and eastern Australia.

Before leaving that point, however, it should be noted that the beam heading toward those observatories in the southern hemisphere is in the range 220–240° east of north. Going to Tables 2 and 3, one sees that more than 12 of the auroral zone and polar paths fall close to those directions. Thus those two observatories could well provide some magnetic information that would be relevant to LP propagation along those paths. By the same token, the concentration of observatories in Europe could be of value in regard for extreme long paths to the Black Sea and beyond. Those paths, however, pass across the southern Indian Ocean where the *Ap* network lacks coverage. The same is true for the paths going eastward past the southern tip of South America, toward Sri Lanka, India, Mauritius, and Reunion Islands, the *Ap* network lacking coverage in that area as well.

Given that discussion, what is needed is a set of magnetic indices based on a more balanced network, and one has been available since 1968 [*Mayaud*, 1968], termed the *Am* network and shown in Figure 8. That network evened out the distribution of observatories in the northern hemisphere, increasing the number to twelve, and introduced seven additional observatories in the southern hemisphere. The observations from

Northern Hemisphere Observatory	Code	Corrected Geomag. Latitude
Magadan	MGD	53.8°
Petropavlovsk	PET	46.4°
Memabetsu	MMB	37.4°
Podkammenkaya	POD	57.2°
Sverdlovsk	SVD	52.2°
Witteveen	WIT	50.2°
Hartland	HAD	50.0°
Niemegk	NGK	48.8°
Ottawa	OTT	58.9°
Fredericksburg	FRD	51.8°
Victoria	VIC	53.9°
Tucson	TUC	39.7°

Southern Hemisphere Observatory	Code	Corrected Geomag. Latitude
Eyrewell	EYR	50.2°
Lauder	LAU	37.7° [?]
Toolangui	TOO	48.0°
Canberra	CAN	45.2°
Gnangara	GNA	44.1°
Kerguelen	PAF	58.8°
Crozet	CZT	52.4°
Hermanus	HER	41.1°
Argentine Islands	AIA	49.7°
Trelew	TRW	27.8°

FIGURE 8. Magnetometer sites in the *Am* network in 1988. From *Menvielle and Berthelier* [1991].

that network are more worldwide in nature than from the *Ap* network and are presented in much the same form, a three-hour index *Km* and a daily index *Am*.

The additional observatories in the southern hemisphere provide magnetic observations in the vicinity of those auroral zone paths in the present study where none was available with just the *Ap* network. But beyond that, with its greater coverage the *Am* network is more sensitive to small or local geomagnetic disturbances, some of which might be missed by the *Ap* network. As a result, the distribution of daily values for *Am* for a given period of time would make the geomagnetic field appear more disturbed than for the same range of *Ap* indices.

Rather than get involved in the basic definitions and scaling techniques for the two indices, a more direct way to appreciate their relationship and differences is by examining a graphical display of *Am*-*Ap* pairs for the days in a period of time, say two years as in Figure 9. From that figure it is seen that there is a good correlation between the indices, 0.96 from a linear regression analysis. Further, the figure shows that for a day with a modest level of activity, say an *Ap* value of 30, the corresponding *Am* value is about 42, and when activity reaches storm proportions, say an *Ap* value of 50, the corresponding *Am* value is about 70.

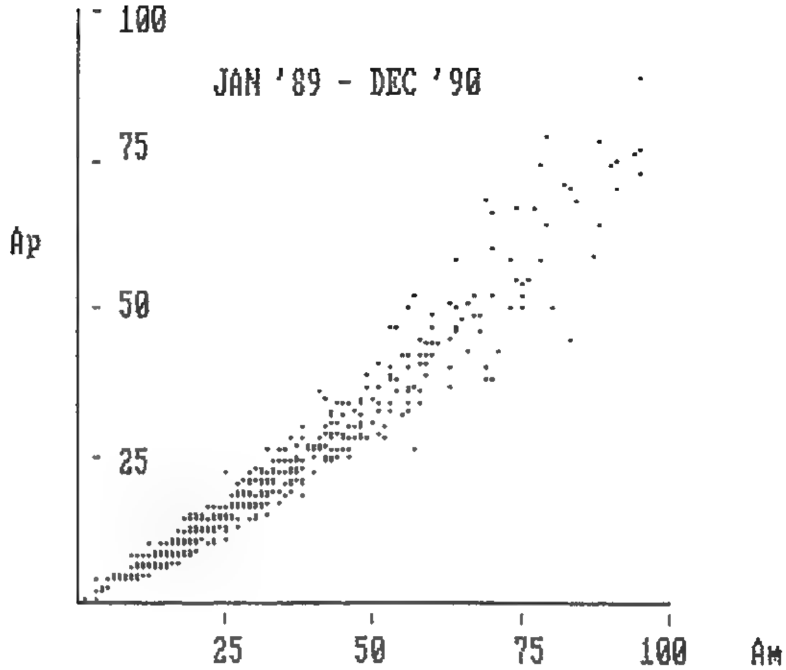


FIGURE 9. Scatter plot of daily *Ap-Am* pairs for a two-year period, January 1989 through December 1990.

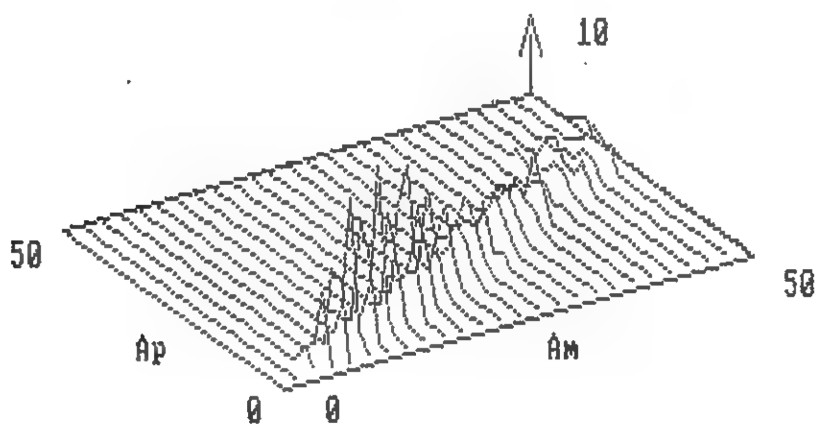


FIGURE 10. Three-dimensional plot of the *Ap-Am* pairs at times of low magnetic activity.

Figure 10 shows the first part of Figure 9, where many data points fall on top of each other, but in more detail by plotting the number of data entries per *Am-Ap* point in the vertical direction. From this plot it is seen that the correlation between *Ap* and *Am* is better at these levels of activity than for extremely disturbed conditions. True, values of *Am* run about 40% higher than the simultaneous values of *Ap*, but the two indices track rather well and with a limited scatter.

From the standpoint of principle it would be more desirable to use indices from the *Am* network, with its extended distribution of magnetometers, in examining magnetic disturbances of LP propagation. As a practical matter, however, the application of those results would be difficult to bring down to the level of everyday operations. Part of this is due to the fact that the *Am* network is not well known outside the tight circle of professional geomagneticians. Further, even though it is prepared under the auspices of IAGA by the Institut de Physique du Globe in Paris, the assembly and analysis of data from a far-flung network takes a good deal of time. As a result, the tables for the *Km*, *Am* indices reach NOAA about 2–3 months after

data collection is completed.

On the other hand, the Ap index is better known, and there is the further advantage to the DXer that estimates of Ap are forecast three days in advance on the NOAA BBS. With the strong statistical correlation between Ap and Am shown in Figures 9 and 10, one can have confidence in making use of the Ap index. Thus if the DXer has a sense of the Ap values that will support propagation, it should be possible to adopt a plan of operation, be it for contesting or DXing, that takes into consideration possible changes in conditions.

With those remarks, the discussion of geomagnetic indices is concluded, and from this point onward only the Ap index will be used in the analysis. Those who are interested in the question of three-hour K indices and daily A indices would do well to read the article by *Menvielle and Berthelier* [1991]. In addition, it might be of interest to review the other geomagnetic data that the NOAA BBS provides: K and A indices from over 20 observatories, albeit usually 3–4 days after the fact and without any sort of overall analysis or interpretation.

PART 3

3.1 Data from the Two Ionospheric Seasons

In examining the effects of geomagnetic disturbances on LP propagation, we should first summarize the results for the various paths and seasons. Thus, going to the spring/summer season, a total of 669 LP contacts were made in that period: 309 on auroral zone paths (including 64 to Crozet Island), 137 on polar paths, and 223 on extreme long paths. For a given type of path there was the possibility of one or more contacts during an LP session, depending on propagation and the usual competition for DX contacts. For those reasons, some days went by without a single contact on a given type of path or, more often, at least one and maybe more contacts.

In order to display the results from the first 168 days of the study without giving undue weight to days with a large number of LP contacts, the results are shown below by dividing them into three categories, paths which go through the southern auroral zone, or paths which also go cross the polar plateau, and then those which went beyond Eastern Africa and the Indian Ocean area into Europe. Thus Table 5 gives the number of days with no contacts, one contact, and more than one contact per LP session.

TABLE 5. Spring/Summer Contacts by Path.

Spring/Summer Path	Contacts/Session		
	0	1	> 1
Auroral Zone	35	47	86
Polar	96	37	35
Extreme Polar	77	36	55

So the fraction of days with one or more contacts on an auroral zone path is given by the ratio $(47+86)/168$, corresponding to 79% of the days. By the same token, on 43% on the days one or more contacts were made on polar paths and 54% of the days with one or more extreme long-path contacts.

In the second half of the LP study there were a total of 1,011 contacts: 125 contacts on auroral zone paths, 56 on polar paths, and 830 on extreme long paths. On a daily basis, there were 171 active days in the second part of the study; the LP contacts were distributed among the various paths as shows in Table 6.

TABLE 6. Fall/Winter Contacts by Path.

Fall/Winter Path	Contacts/Session		
	0	1	> 1
Auroral Zone	97	43	31
Polar	123	42	6
Extreme Polar	15	8	148

From Table 6, the percentage of days with one or more contacts on the various paths are 43%, 28% and 91%, respectively. But, from the distribution of days shown above, it is clear that a very significant shift took place in the second part of the study, contacts on the polar paths becoming far fewer in number while the percentage of days with multiple contacts on extreme polar paths reached a high value, 87% as compared to the earlier value of 33%.

The next step in the analysis is to see if making LP contacts was affected by geomagnetic activity. For the first part of the study, Table 7 shows a breakdown of the days when LP contacts were made according to paths and levels of magnetic activity, ranging from quiet to major storm. The second part of the study is given in the same format in Table 8.

TABLE 7. Long-Path Sessions, April–September.

Ap Index	Days	Auroral Zone Contacts/Session			Polar Contacts/Session			Extreme Polar Contacts/Session		
		0	1	> 1	0	1	> 1	0	1	> 1
0–10	51	7	13	31	15	16	20	18	17	16
11–20	39	6	11	22	22	11	6	16	5	18
21–30	31	3	11	17	21	4	6	16	7	8
31–40	16	4	4	8	12	2	2	6	4	6
41–50	10	1	4	5	6	3	1	5	1	4
51–60	7	4	1	2	7	0	0	5	1	1
> 60	14	10	3	1	12	2	0	10	2	2

TABLE 8. Long-Path Sessions, October–March.

Ap Index	Days	Auroral Zone Contacts/Session			Polar Contacts/Session			Extreme Polar Contacts/Session		
		0	1	> 1	0	1	> 1	0	1	> 1
0–10	47	26	10	11	34	11	2	0	0	47
11–20	57	31	15	11	35	18	4	0	1	56
21–30	31	16	10	5	23	8	0	0	4	27
31–40	12	8	2	2	10	2	0	2	2	8
41–50	5	2	2	1	5	0	0	2	0	3
51–60	7	5	1	1	5	2	0	3	1	3
> 60	12	8	4	0	12	0	0	9	0	3

Inspection of the two tables shows a distinct change in the character of LP propagation between the two ionospheric seasons. But before discussing those observations it is important to consider the magnetic conditions which prevailed when they were obtained. As noted in the discussion following Table 5, the spring/summer season was the stormier of the two seasons with minor and major magnetic storm conditions on 28% of its days as compared to 21% for the fall/winter season. Further, examination to the extreme values of *Ap* in Figure 2 shows that not only were storm conditions more prevalent in the spring/summer but they also involved higher values of *Ap* than in the fall/winter season.

Turning now to Tables 7 and 8, a striking difference is seen in comparing results for the two seasons. Thus, in spite of the fall/winter season being less disturbed, there is a marked change in the effectiveness of LP propagation. the auroral zone and polar paths deteriorating even with non-storm conditions. At the same time, however, LP propagation improved greatly on the extreme long paths.

The spring/summer results in Table 7 show a negative correlation with magnetic activity, propagation deteriorating particularly with high values of *Ap*. In itself that is nothing new. But the fall/winter season is different because of another factor, ionospheric absorption on the paths. Thus propagation on extreme long-paths improved because, with winter in the northern hemisphere, the sun was at a lower angle in the sky when LP opened. Indeed, the "reach" of ELP signals into Europe became greater, shifting from the Crimea, the Ukraine, and the Balkans in the spring/summer season into western and northern Europe, say west to the British Isles and north into Scandinavia.

During the fall/winter season, ionospheric absorption increased particularly on paths across the Indian Ocean. While contacts were made with Mauritius (3B8), Reunion Island (FR5), and the like in the first month after the autumnal equinox, they soon came to a halt and did not begin again until a month before the spring equinox. Those paths are in the polar category, and the same experience was true with paths

to India and Sri Lanka, in the auroral zone category. The reason, of course, is that with the start of the spring/summer season in the southern hemisphere the paths from northwest USA to those regions became illuminated, and signal strengths reduced to a vanishing level because of the ionospheric absorption.

The statistics in Table 8 also suggest a deterioration of propagation on paths in the auroral zone category. With the exception of paths to India and Sri Lanka just discussed above, the remainder of the paths in Table 2 are to Crozet Island and locations in southern Africa. The case of Crozet Island is a special one, especially with the frequent presence of FT4WC on the band and then followed by cessation of his operations in November '91.

Now a review of my log shows that contacts with southern Africa did decrease during the fall/winter season but not cease altogether like with stations in the Indian Ocean area. More specifically, contacts with southern Africa were made at an average rate of one per day in the first and last months of the fall/winter season and at about half that rate during the intervening four months. But the contacts were not marginal since there seemed to be no significant decrease in signal strength over the entire period. That being the case, one has to look for other reasons than the onset of ionospheric absorption, particularly during that period since paths from the Northwest to Africa were in darkness except at the two ends.

Several factors come to mind in explaining the decrease of contacts to southern Africa, some physical in nature and others of human origin. From the physical standpoint, there is the question as to the extent to which summer weather conditions affect amateur activity in the southern parts of Africa. That region, along with South America and East Indies, has an extremely high seasonal rate of occurrence of thunderstorms. If nothing else, electrical storms at the rate of one every day or two would surely be intimidating, particularly with regard to the safety of electronic equipment connected to ungrounded antennas or the power lines.

That aspect is local to particular times, regions, and topographies. Something of a broader nature is the radio noise generated by electrical storms. Global studies of the distribution of noise have divided areas of the earth according to zones, 1 through 5. The regions most distant from thunderstorm areas and which receive little atmospheric radio noise by skywave propagation are classified as zone 1. By that classification scheme, regions where thunderstorm activity is most frequent are in zones 4 and 5. In that regard, southern Africa lies within zone 4 during the months of December, January, and February.

In addition to the zone in which a receiving station is located, another important item is the radio frequency distribution of atmospheric noise [*Davies*, 1990] with the time of day. The general features of the distribution distinguish between daytime and nighttime, and there are finer differences according to zone and local times. But the essential features show a high level of noise around 14 MHz, day or night, for zone 4 regions. Thus the smaller number of contacts with stations in southern Africa may find some explanation in thunderstorm activity and the radio noise or static crashes that are propagated in from surrounding regions. Indeed, this is attested to by recent accounts [*DX Magazine*, April, 1992] of DXpeditions to southern Africa, say Malawi.

As for human factors, it should be noted that the distribution of LP contacts shown in Figure 1 shifts to later times in UTC with the onset of the fall/winter season. In that regard, I have a suspicion that not all DX operators are aware of that shift and do not adjust their operating hours accordingly. I say that since in the course of this study I had occasion to be called frequently, almost on a schedule, by an operator in Africa. He always called me just when LP began to open up here and signals were growing in strength. It was with some difficulty that I got him to shift to a later time. Thus, if operators did not understand the need to shift operating times with season, they would find LP propagation deteriorating at the same time of day and come to the erroneous conclusion that LP propagation was closing for the season.

Also, the shift of LP to later times in the fall/winter season brings the time of LP openings closer to the dinner hour in Africa. In addition, there is the matter of personal comfort in the hot, humid climate along the coastal regions near the Tropic of Capricorn. While I have no first hand experience in the matter, I would think that sitting on the veranda, sipping a glass of iced tea, would have its attractions in the late afternoon, perhaps even more than operating on 20-meter CW looking for LP contacts into North America.

All in all, I can find no plausible explanation in pure ionospheric terms for the smaller number of contacts with southern Africa during the period from November to February. I have to leave it there, leaning toward the thunderstorm explanation, but would be interested in learning the views of others on the matter. For me the effect is real but puzzling.

To bring this section to a conclusion, earlier a negative correlation between LP and magnetic activity was mentioned. However, the data in Tables 7 and 8 show that ionospheric absorption can be a factor,

depending on the paths involved. Thus, in examining the question of a negative correlation, one should look at specific paths, as free of absorption effects as possible and with a large data sample. This will be done in the next section, using auroral zone paths in the spring/summer and extreme long paths in the fall/winter season. Of course, the results obtained apply only to paths from the Pacific Northwest.

A related question, the effect of magnetic activity on sub-auroral zone paths is examined. That was carried out for the spring/summer season also. Since such paths were not possible from this location, the effects of magnetic activity were determined by reconstructing the spring/summer season using other amateurs' log data for sub-auroral paths between South Africa and Southern California.

3.2 Statistical Aspects of LP and Magnetic Activity

The previous discussion did not bring out in a quantitative fashion the effect of magnetic activity although the data entries in Tables 7 and 8 suggested an anti-correlation between LP propagation and magnetic activity. That idea is not new, by any means, ionospheric disturbances having long been associated with geomagnetic storming. But it has been more a matter of impressions than one having any sort of quantitative basis.

Now one can start with "impressions" with the present database. showing how the fraction of QSO's on the various paths compare with the fractions of days with differing levels of geomagnetic disturbance. Before doing that, however, it should be noted that for amateur radio purposes long-path propagation is measured by the ability to make such contacts on a given day. Indeed. making LP contacts in the course of time means that we may use the daily rate of making contacts as the measure for our analysis.

But the actual rates used in examining LP propagation may be influenced by many factors, not the least of which is operating style. Thus the least "impressionistic" variable or measure of LP propagation would be a quantity or rate which is simple enough as not to be affected significantly by operating style, say some minimum number of contacts per LP session which amounts to something like a "Yes-No" statement.

If one broadens the use of the database to the actual numbers of contacts per day or LP session, then some restrictions should be put on the method, say using only data from a particular type of path. Beyond that, the data should be limited to a single ionospheric season because of the size of the sample. For example, the extreme long-path contacts in the fall/winter season lend themselves to a statistical analysis because of their large number; that cannot be said for those on that path in the spring/summer season.

And there are other factors that should be kept in mind, not the least of which is the competitive circumstances for contacts with a given type of path or ionospheric season. This concern applies particularly to the spring/summer season where contacts into the Indian Ocean were highly competitive. Thus it would be a major error to try any sort of analysis with that portion of the database as the numbers are small and the results would be influenced by factors which are difficult to evaluate. On the other hand, competition for contacts with Europe in the fall/winter season was essentially non-existent, and that large database can be used in a statistical analysis with a minimum of concern about external bias or unusual influences from operating style.

With those caveats, let's proceed to look at the database from different perspectives. First, consider Figure 11 which gives the percentage of days of different levels of magnetic disturbance and the percentage of contacts in the spring/summer season on the three different types of paths. There, for example, it is seen that during quiet conditions (Ap 10 or less), the percentage (39%) of QSO's completed on auroral zone paths is out of proportion to the percentage (28%) of days of magnetic quiet. At the other extreme, for storm conditions (Ap greater than 50), one sees the percentage (2%) of QSO's completed is considerably less than the percentage (8%) of days with those conditions.

From that one can conclude there is some cross-over point or level of magnetic activity at which propagation begins to suffer. But that approach only deals with apparent success and ignores failure as well as real success, the complement of failure. In the next few paragraphs, that will be corrected using methods which range from simple to sophisticated.

As a first step, consider the following which is based on elementary probability considerations. Thus we will make use of those data entries in Tables 7 and 8 but in a rather simplified form. In particular, for each range of Ap let's use two values of a variable, either $Q = 0$ for failure or $Q = 1$ for success in LP propagation.

Thus $Q = 0$ will be used for those days when no contact was made during an LP session while $Q = 1$ is used for days when one or more contacts were made. For the 0–10 range of Ap in the auroral zone part

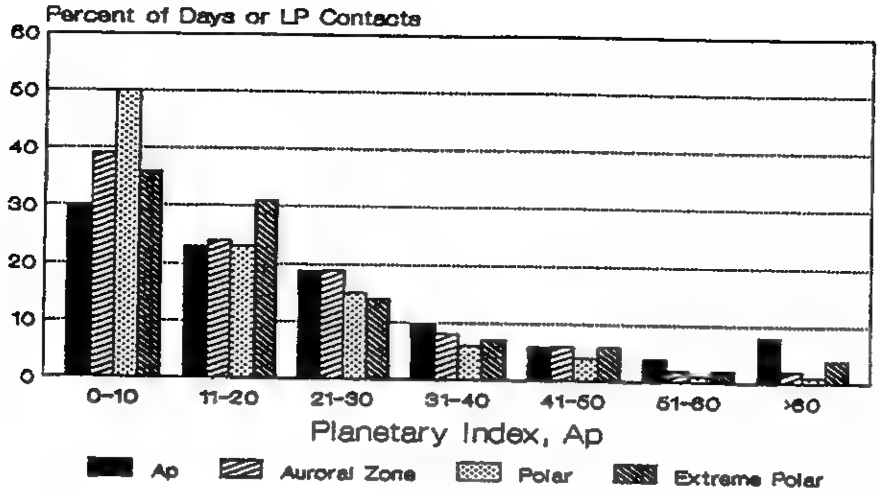


FIGURE 11. Distribution of magnetic activity and long-path contacts. April 1, 1991, through September 21, 1991.

of Table 7, the value for success adds up to 44. In a similar fashion, all the rest of the entries in the other paths for the spring/summer period can be modified, the values for "1" added to those for "> 1."

Now if LP contacts were made on each of the 168 days, the total success value would be 168.00 or the success would be 1.00 for each day. Correspondingly, the apparent success value would be less than 1.00 per day if there were any days of failure in the period. Thus, for the *Ap* range of 0 to 10 in Table 7, the apparent success value for auroral zone contacts during the 168 day period was 44/168 or 0.26. But *Ap* was in that range during 51 days or 30% of the time so if those conditions prevailed all the time, the success value probably would be 44/51, 0.26/0.30, or 0.87.

If one proceeds through the rest of the auroral zone part of Table 7, the other corrected success values would be 0.85, 0.91, 0.73, 0.78, respectively, as the *Ap* range goes from 11–20 on to 41–50. For storm conditions, with *Ap* above 50, the sample of days is small so, lumping them together, one obtains a value of 0.35 for the success during storm conditions. The variation of those values indicates that using ideas based on probability there is a small negative correlation between success in LP propagation on auroral zone paths and *Ap*, the value for success decreasing somewhat as *Ap* increases, at least for *Ap* values below those typical of major magnetic storms ($Ap > 50$).

Similar calculations were done for the polar path and extreme long-path entries in the spring/summer period. But for each day, all those paths were potential sources of LP contacts. Since the LP openings essentially occur in consecutive order, from auroral zone to polar and then extreme polar (as will be discussed later), one can think of the total adjusted value for "success" for a complete LP session as the sum of the different values. These results are shown in Figure 12 where they are "stacked" so as to give graphic representation to the negative correlation mentioned above, "success" in the spring/summer season decreasing as *Ap* increased.

If that discussion based on simple probability arguments does not convince you of the negative correlation between LP propagation and magnetic activity, there is another approach — "best case" vs. "worst case" — that is used often by statisticians as a diagnostic tool. For the sake of variety, let's apply it to the extreme long paths (ELP) during the fall/winter season. As noted in comparing Tables 7 and 8, that period was dominated by ELP contacts, giving a large database to work with.

If one takes the entire fall/winter season, there were 830 ELP contacts in that period, the average number of ELP contacts amounting to 4.9 per day. Of course, there was a variation of *Ap* during that period so one can look at that in relation to all those contacts. In order to do that and make some sense of the anti-correlation between magnetic activity and LP propagation, one can sort the days in the fall/winter season according to the number of contacts per LP session, ranging from zero to 14. This is shown in Table 9.

Now statisticians suggest that in looking for positive or negative correlations it would be informative to compare the two extremes of the distribution: the magnetic activity for the lower group, say the first 49 contacts when the ELP QSO/day was below 4, and the uppermost group, say the last 45 contacts when the

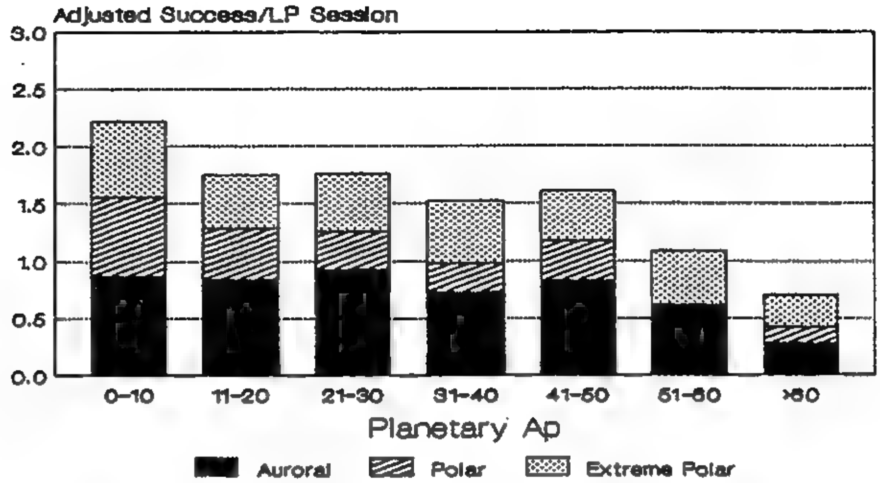


FIGURE 12. Adjusted success/LP session vs. Ap index ranges. April 1, 1991, through September 21, 1991.

TABLE 9. Fall/Winter Days with a Given Number of ELP Contacts.

ELP QSO/Day	Days	ELP QSO/Day	Days	ELP QSO/Day	Days
0	15	5	30	10	4
1	8	6	27	11	1
2	12	7	19	12	1
3	14	8	12	13	0
4	20	9	8	14	0

number of ELP QSO/day was above 6. Once the days are identified the Ap values in each group can be averaged for comparison. In this case, the average Ap value for the lower group amounted to 42.9 while that for the upper group was 13.5.

The question then shifts to the significance of that difference, some 29.4 units of Ap. Here, one looks at the average Ap value for the period, 23.4, and notices that for the lower group with the fewest QSO's per LP session the average is 19.5 units of Ap above the average while that for the upper group, with the greatest number of QSO's per LP session, is 9.9 units below the Ap average.

Now if the number of ELP QSO's per day were completely unrelated to the level of geomagnetic activity, as given by Ap, the two groups of days would be intermingled and the average values of Ap for each of the two groups would be close to that for the sample as a whole, 23.4 units of Ap. Thus the separation given above points to heightened magnetic activity having an inhibiting effect on the number of ELP QSO's possible in a day, a negative correlation. The grouping of the data with respect to Ap can be seen in Figure 13, those days with 6 or more contacts per day lying above the axis and those with less than 4 per day below it. If one wants to be even more quantitative in the matter, more elaborate statistical methods are required.

One way of proceeding is to regard the magnetic index Ap as a continuous variable but LP propagation as a dichotomous variable with just two values, $V = 1$ and $V = 0$, depending on whether contacts in an LP session were more numerous or less numerous than a specified number of contacts per day, say 5, which is close to the average value for the period. For this situation, the methods of point biserial correlation are appropriate and provide a value for the correlation coefficient between the two variables.

In applying this technique [*Walker and Lev*, 1953] to ELP contacts in the fall/winter season, we begin by using 5 contacts per day as the dividing line. For that choice the database shows that in 171 days there were 102 sessions (N_1) with 5 or more LP contacts ($V = 1$) and 69 sessions (N_0) with less than 5 contacts ($V = 0$). If one renames Ap, now calling it Y, then one first needs to compare the difference between the

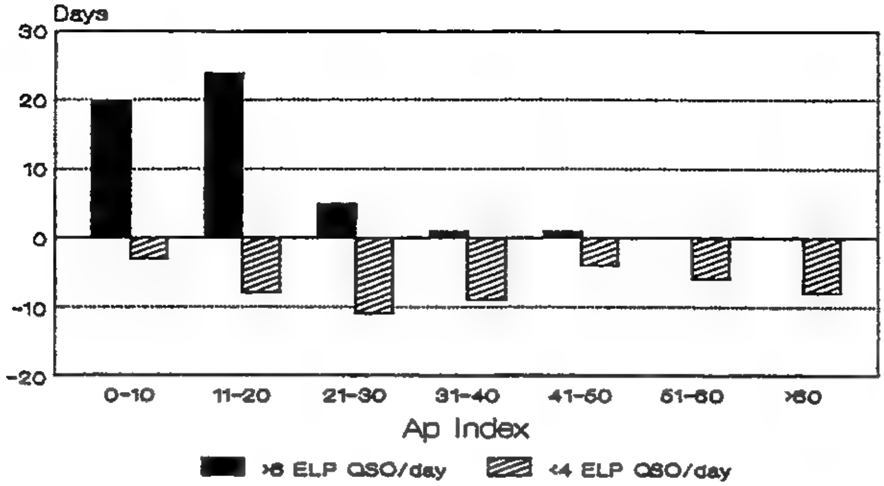


FIGURE 13. Distibution of long-path contacts vs. *Ap* index ranges for < 4 LP QSO/session and > 6 LP QSO/session.

average value of Y for days with $V = 1$, $\overline{Y}_1$, and the average value of Y for days with $V = 0$, $\overline{Y}_0$, to the standard deviation of Y, SD_y:

$$(\overline{Y}_1 - \overline{Y}_0)/SD_y$$

For the 171 days in the fall/winter season calculations show that $\overline{Y}_1 = 16.2$ and $\overline{Y}_0 = 33.9$ while $SD_y = 22.0$ and the ratio shown above is -0.80. The point biserial correlation coefficient is obtained by multiplying that number by a factor involving the total size of the sample N and its division into categories, N_0 and N_1:

$$\sqrt{(N_1 * N_0)/(N * (N-1))}$$

This factor is 0.49 so the biserial correlation coefficient is $r_{pb} = -0.39$, indicating a negative correlation between magnetic activity, as given by *Ap*, and LP propagation when 5 contacts/session was used as the reference. Now that correlation coefficient is not as striking as -1.00, which implies a strong negative correlation, nor is it 0.00, which would mean no correlation at all. In short, it is a middle value which would mean that there is some negative correlation in effect when the *Ap* index rises, but certainly not a positive correlation which would show more ELP QSO's when *Ap* increases.

By way of interpretation, the moderate negative correlation value results from the fact that the average values of *Ap* for $V = 1$ and $V = 0$ were separated by more than one standard deviation, at least for a 60% : 40% division of the sample. Beyond that, if the negative correlation were real as the data and experience suggest, it should be evident for different divisions of the database. And indeed that proves to be the case as a significant negative value of the correlation coefficient of about -0.44 was obtained when the database was divided at 4 contacts/session (71% : 29%).

Finally, having used both simple and complicated methods to explore the correlation between magnetic activity and propagation, we could take a less conservative approach and use QSO's/session instead of the success/failure approach to the data. The success/failure approach is more appropriate to a study of HF propagation, but using QSO data relates more closely to amateur radio experience; however, it should be understood that the results will be more subjective because differences in operating style may influence the results. Be that as it may, the adjusted QSO rates for LP sessions in the spring/summer season are given in Figure 14.

It is left to the reader to suggest factors other than operating style which are non-physical in nature yet contribute to the changes in QSO rates as *Ap* increases or decreases. Certainly there is the matter of persistence, previous low values of the *A* index bringing on more of the same and DXers out in droves. And

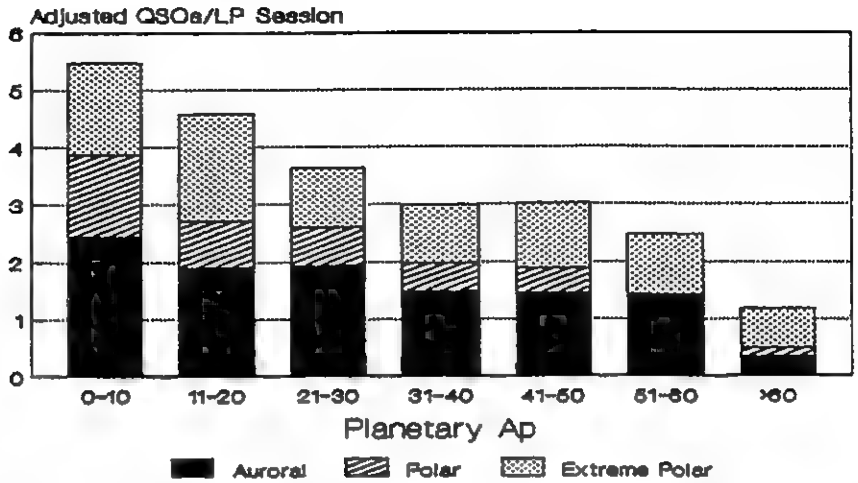


FIGURE 14. Adjusted LP QSO/LP session vs. Ap index ranges, April 1, 1991, through September 21, 1992.

similarly, high values of the A index don't decay away at once and have a rather discouraging effect. Those are obvious factors but certainly there are others.

3.3 Change in Origin for Great-Circle Paths

Having made the point that seasonal variations may be somewhat different at lower latitudes, say in the Los Angeles area, one can examine whether similar results might be expected for disturbances due to solar outbursts. To that end, details of the paths in Tables 2 and 3 were calculated again for an origin at Los Angeles. In contrast to the seasonal effects where the shift in origin would have a small effect on the time when signal paths are lost, a southern shift in origin has a large effect on the categories of paths when viewed using geomagnetic coordinates.

Thus, using Los Angeles as the origin, the great-circle paths of the stations in Table 2 are shifted into the sub-auroral category, the only exceptions being 4S7 and VU2 which still remain as auroral zone stations. As for the stations in Table 3, great-circle paths for 3B8, FR5, FR5/T, and 3B9 remain in the polar category while the others (FH, D6, and 5R) were changed to the auroral zone category.

While the distances are not particularly different using Los Angeles as the origin, perhaps 1,500 km shorter on the average, the extreme geomagnetic latitudes are quite different, those in Table 2 average 46.7° for the Los Angeles area compared to 66.1° from this QTH, and those in Table 3 are 12° lower on the average for the same comparison.

That very result goes to point out the shortcoming of the present study from the northwest corner of Washington. Thus, given the distribution of land masses and population, it is not possible to directly explore the influence of magnetic activity on sub-auroral paths by operating from this far north. But it seemed that the matter could be explored in another way; in particular, with a conservative selection criterion like success/failure used above, one could avoid bias in the results and perhaps synthesize a magnetic activity table for sub-auroral paths by bringing together log data from a number of different operators.

Thus a call went out to long-path operators in the Los Angeles-San Diego area and South Africa for log data (date, time, and call) for contacts during the spring/summer season. The selection criterion was quite simple, just one or more contacts on a sub-auroral path in the same time interval of UTC as in the study. The response was quite gratifying, and when the LP data was finally collected from thirteen operators, four in southern California and nine in southern Africa, another category was added to Table 7, as shown in Table 10.

It should be noted that in the sub-auroral category, all the days listed as "≥ 1" contacts were from log data while those days listed as "0" contacts and shown in parenthesis were inferred as days of failure. While log data received for the spring/summer season added up to 157 days, 17 days were not reported with any

TABLE 10. Long-Path Sessions, April–September, Including Sub-Auroral Paths.

Ap Index	Days	Sub-Auroral Contacts		Auroral Zone Contacts		Polar Contacts		Extreme Polar Contacts	
		0	≥ 1	0	≥ 1	0	≥ 1	0	≥ 1
0–10	51	(2)	49	7	44	15	36	18	33
11–20	39	(4)	35	6	33	22	17	16	23
21–30	31	(1)	30	3	28	21	10	16	15
31–40	16	(3)	13	4	12	12	4	6	10
41–50	10	(2)	8	1	9	6	4	5	5
51–60	7	(1)	6	4	3	7	0	5	2
> 60	14	(4)	10	10	4	12	2	10	4

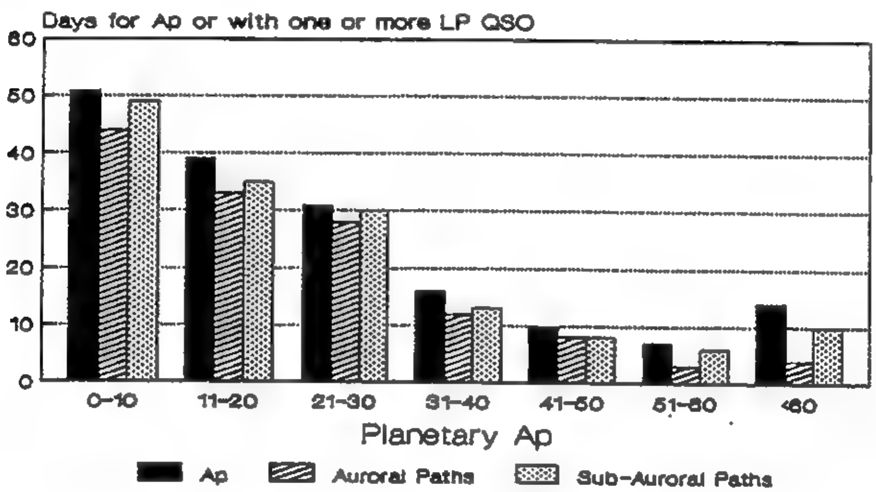


FIGURE 15. Number of days and sub-auroral and auroral zone contacts vs. *Ap* index ranges, April 1, 1991, through September 21, 1992.

LP contacts; six days were omitted for those times when contests were held, making the times and conditions for the remaining sub-auroral paths exactly the same as the days for the other paths in Table 7.

Inspection of the sub-auroral and auroral entries in Table 10 shows a close similarity in the number of contacts per LP session as magnetic activity increases until major storm conditions were encountered when the sub-auroral paths became far more successful. This is shown more clearly in Figure 15, which also includes the number of days for each *Ap* range.

The success factors on sub-auroral paths are 0.86, 0.88, 0.94, 0.79, and 0.69, respectively, as *Ap* goes from 0–10 to 41–50. Then the sub-auroral paths are more successful than the auroral paths during storm conditions, the factor being 0.83 as compared to 0.35 for auroral zone paths. These factors during storm conditions, while significant in the discussion, have greater uncertainties as small samples are subject to large statistical variations.

While having this result come forth from the efforts of a single operator at one location would be more desirable, it still has merit as it was arrived at by a fairly conservative procedure. In addition, the same amateur populations and comparable numbers of contacts were involved. In any event, the differences in success at storm levels of activity cannot be attributed to a lack of effort on my part on auroral zone paths. Except for the days during the magnetic storms of June and July, LP signals were heard and stations called from this site. But signals were weak and contacts simply proved to be impossible.

Thus the result provides a quantitative indication that lower latitude paths are less susceptible to disruption than other paths which reach into higher magnetic latitudes. Previously, all that was available on that topic was of an anecdotal nature so, to that extent, the present results do represent an improvement.

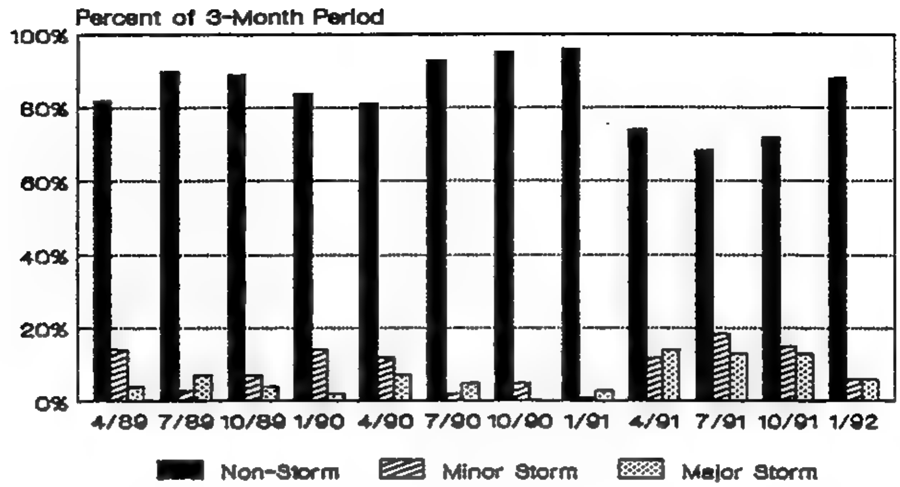


FIGURE 16. Levels of magnetic activity in three-month intervals, April 1, 1989, through March 31, 1992.

As for its physical basis, it is due to the fact that the ionosphere on sub-auroral paths is at the feet of magnetic field lines which only go out 2–3 earth radii while that for auroral paths involves field lines going out 6–7 earth radii. The latter are more vulnerable to the effects of the impact of solar plasma on the magnetosphere.

Now having shown the overall features of the spring/summer and fall/winter seasons of the study, as summarized in Tables 7 and 8 above, it is of interest to put the study in perspective. In particular, since the study was conducted from month 55 to 67 in Cycle 22 and geomagnetic variations were of considerable importance during the entire study, one should look to see how representative the study might be during Cycle 22. To that end, the magnetic index *Ap* was analyzed in three-month periods starting in April '89 and running through the end of March '92.

The analysis involved determining what percentage of days in each of the three-month periods could be described as non-storm as well as minor and major storm conditions. These results are shown in Figure 16, and in viewing this result it should be kept in mind that the time of solar maximum was in July '89.

The principal feature seen in this bar-graph display is that non-storm conditions dominated, being present more than 80% of the time before the present study began. While it is true that storm conditions vary in importance over the course of time, the present study had more storm activity than the previous two years. The most notable times covered by this figure were the intense geomagnetic storms associated with flare outbursts in '89 and '91. But it should be noted that a good portion of the magnetic activity in the present study came from another origin, solar plasma streams from coronal holes.

3.4 f_oF_2 Maps and Long-Path Propagation

One cannot discuss propagation, either short- or long-path, without considering the properties of the ionosphere at a given time of day, month, and sunspot number. After all, successful propagation depends on wave refraction back to earth, time and again along a path, and adequate signal strength depends on the solar illumination along the path. Thus a knowledge of the state of the upper and lower regions of the ionosphere along a proposed path is essential in order to see whether a viable situation presents itself or not. To that end, one needs ionospheric maps for the critical frequencies of the F layer for the upper reaches while the lower reaches are dealt with using the spatial relationship of the terminator and the path.

When it comes to ionospheric maps, those of the readers who were active DXers before propagation programs on computers became so readily available know what I am talking about — those MUF(ZERO)F2 and MUF(4000)F2 maps that were prepared from years of ionospheric sounding and then published by the Department of Commerce back in the '60s and '70s. They gave a mapping of the monthly median critical frequencies over the world in two hour intervals.

To illustrate the matter, I have chosen two f_oF_2 maps from a paper by *Davies and Rush* [1985], shown

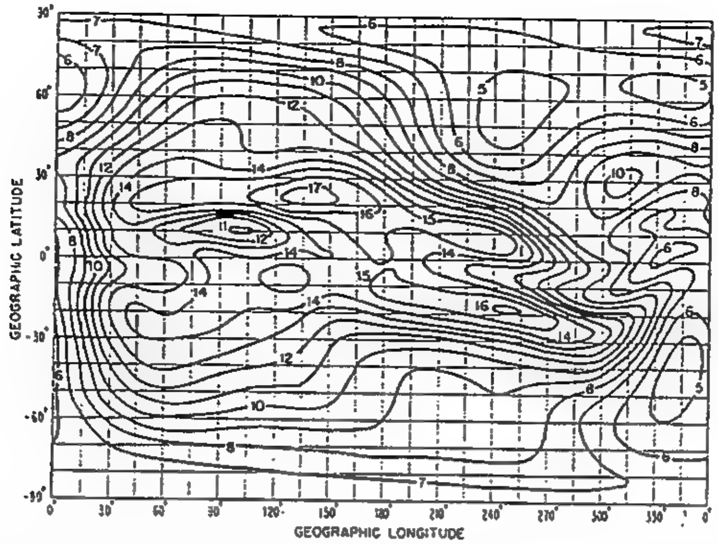


FIGURE 17. Global f_oF_2 map for 0600 UTC, March 1979 (SSN = 137). From *Davies and Rush* [1985].

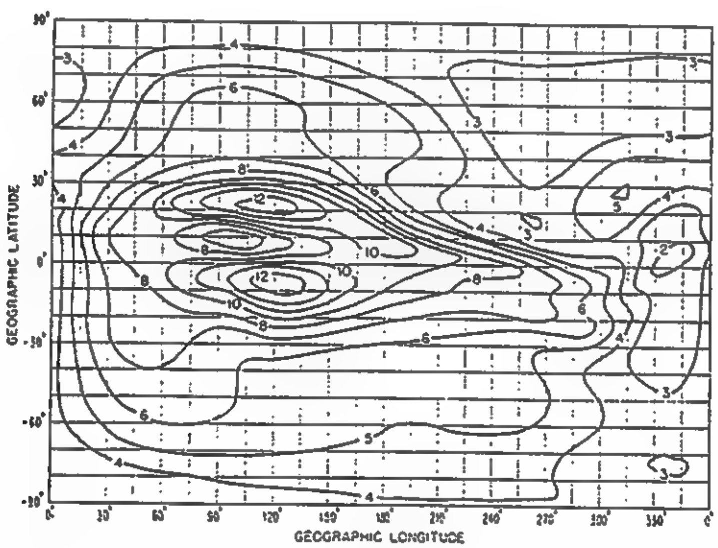


FIGURE 18. Global f_oF_2 map for 0600 UTC, March 1976 (SSN = 12). From *Davies and Rush* [1985].

in Figures 17 and 18. They give global representations of the monthly median value of f_oF_2 for the month of March and years 1979 and 1976, respectively. Those choices highlight the differences in f_oF_2 values and their spatial distributions between times of solar maximum in Cycle 21 in 1979 when the SSN was 137, and solar minimum earlier when the SSN was a mere 12.

Those figures are for 0600 UTC in March when the sub-solar point (local noon) is located at 90° east longitude. The region with full solar illumination lies between 0° and 180° east longitude and darkness between 180° and 360° (or 0°) east longitude. Inspection of those figures shows that the F region retains ionization even after sunset, essentially with electrons stored at high altitudes because of the low number density of atoms and molecules and the low collision rates which lead to electron-positive ion recombination.

In Figure 17, one notes regions where the iso-frequency contours are closely spaced, say around the hours of dawn north and south of the equator and in the early evening hours at equatorial latitudes. These regions correspond to places where the ionospheric electron density shows large spatial changes or gradients. As such,

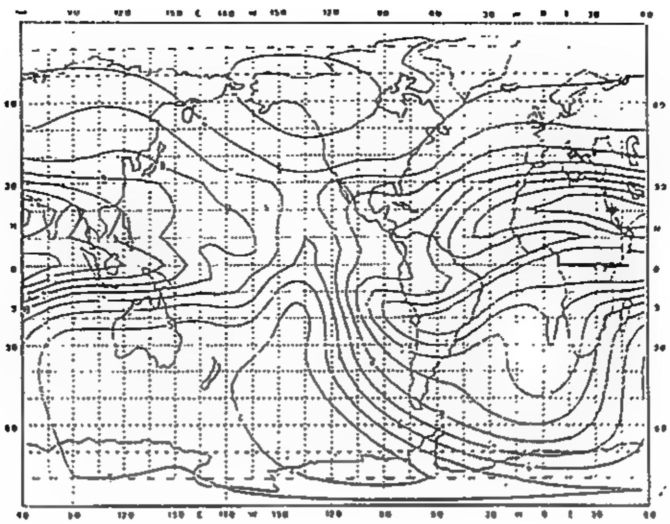


FIGURE 19. Global f_oF_2 map for 1400 UTC, June (SSN = 110). From *Leftin* [1971].

they may have pronounced effects on the refraction of HF waves passing through them. Those situations are best treated by computer modeling, tracing wave propagation through the ionospheric region in question, and they can produce paths longer and shorter than normal, even paths that depart from great-circle directions.

Before leaving these questions, attention should be called to striking differences between the f_oF_2 maps in Figures 17 and 18. In Figure 18, for solar minimum, conditions can best be described as "bleak," showing how low the critical frequencies are around solar minimum as compared to solar maximum, shown in Figure 17. In addition, it is shown how small and limited the ionosphere is at solar minimum as compared to its larger extent around solar maximum. Now in 1992, when we're past solar maximum and facing the prospect of a gradual descent toward minimum, one can see that propagation based on earth-ionosphere hops will suffer, at least on the higher HF bands. That is the case as successful refraction of HF waves at oblique incidence on any point in the ionosphere depends on the operating frequency being less than about three times the local value of f_oF_2. Thus, on the average, 21 MHz refractions would be expected from regions where f_oF_2 is in excess of 7 MHz. Clearly, such a region in Figure 18 is much smaller than found in Figure 17, and DX propagation would suffer accordingly. Of course, this is not exactly news to anyone who has been on the HF bands through a full solar cycle.

Earlier, mention was made of the southern excursions of the great-circle paths relative to the geomagnetic pole. Just as important are the locations of the end-points of the great-circle paths relative to the geomagnetic equator. In that connection, the casual observer might think that every location in Table 2 and Table 3 is in the southern hemisphere. Not so; the fact is that Bangalore, India, and Colombo, Sri Lanka, are about 10–15°north of the geographic equator. But for ionospheric purposes, the important thing is they both are close to the geomagnetic dip equator.

Now I have to digress again. In ionospheric physics there are "equators" and "EQUATORS!" For most ionospheric purposes, one focuses attention on the geomagnetic field near the earth's surface. After all, the F layer is not all that high, about 300 km above the earth. Thus ionospheric electrons released by the flux of solar radiation on the atmosphere are constrained in their motions by the local value of the geomagnetic field at those altitudes.

Having said all that, let's note that in the present LP study there were not only stations to the south of the geomagnetic equator but also stations well to the north that played quite a prominent role. Just to mention a few, I'm speaking of prefixes like DL, F, I, LZ, UA, UB, YU, and those from even further to the north. All those stations are interesting as they make up the ELP category, indicating just how far signals can go with long-path propagation.

But what about all these paths, ending below as well as above the geomagnetic equator? The interesting thing is that they straddle a unique part of the ionosphere, the "equatorial anomaly." That is a region

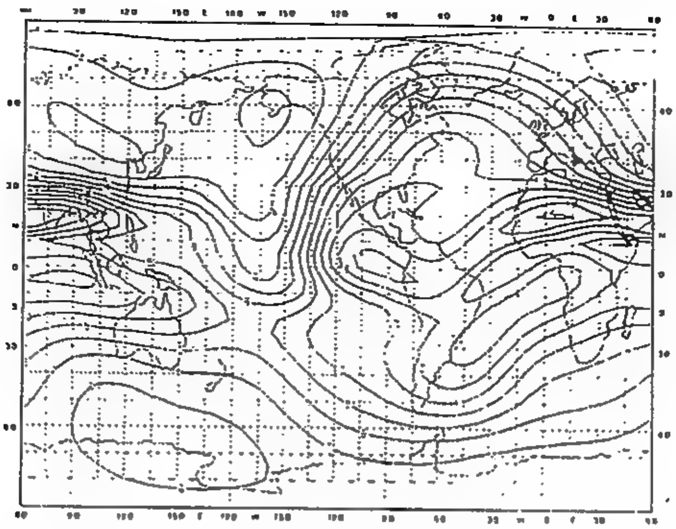


FIGURE 20. Global f_oF_2 map for 1600 UTC, December (SSN = 110). From *Leftin* [1971].

where the quiet ionosphere reaches its greatest heights and electron densities. And it is unusual in a further sense as it involves two regions with large electron density gradients lying about 15° above and below the geomagnetic equator.

But, for our purposes, the interesting thing about the equatorial anomaly is it that represents a region with one category of ionospheric tilts where signals experience marked effects, undergoing successive refractions from the F layer without an intermediate ground reflection. Further, signals may experience a marked focusing, concentrating waves over a small range of distances. and thus giving rise to greater signal strengths than normal. This is treated in *Davies'* book [1965] and includes the results of ray tracing across the anomaly (see his Figure 4.26) which shows a long hop without any intermediate ground reflection.

A good example of this ionospheric feature is shown in Figure 19, the MUF or F2(ZERO)MHz map for 1400 UTC in the month of June when the sun number was 110 (much like in '91). Such data would be obtained from a network of ionosondes sending RF pulses upward and looking for echoes off the F layer. And the map is easy to interpret since the iso-frequency contours show places on the earth's surface where the critical frequency for vertical incidence (f_oF_2) on the highest layer of the ionosphere would be constant. For this month (June) and time (1400 UTC), the critical frequencies are appropriate for a sub-solar point at 30° west longitude and about 23.5° north latitude. Thus the north polar ionosphere would be well illuminated while the south polar ionosphere would be in darkness.

A few paragraphs back, mention was made of ionospheric tilts. Those are regions where the ionosphere undergoes rapid horizontal (or vertical) changes in electron density or, equivalently, show crowding of iso-frequency contours in an f_oF_2 map. Inspection of Figure 19 reveals two such regions, one around the southern tip of Argentina where sunrise is taking place and the other in the equatorial latitudes around Saudi Arabia and India.

A better example of ionospheric tilt regions from the crowding iso-frequency contours is shown in Figure 20, now for the month of December, for 1600 UTC, and with the same sunspot number. With the shift of seasons from summer to winter, the dawn tilt or gradient has moved to the northern hemisphere and is evident by noting the crowded iso-frequency contours on the west coast of the USA, and the other equatorial tilt region is even more pronounced, again around Saudi Arabia and India.

The typical situation for short-path propagation is a series of hops with successive reflections off the ionosphere and then the earth. That idea certainly has its place in LP propagation; however, there are good arguments to also suggest the occurrence of the unique type of reflections mentioned above, two off the ionosphere but without one on the earth in between. Indeed, the best arguments for these circumstances are from cases of extreme LP propagation, as in the present study, as well as around-the-world (RTW) echoes [*Fenwick and Villard*, 1963] of HF signals.

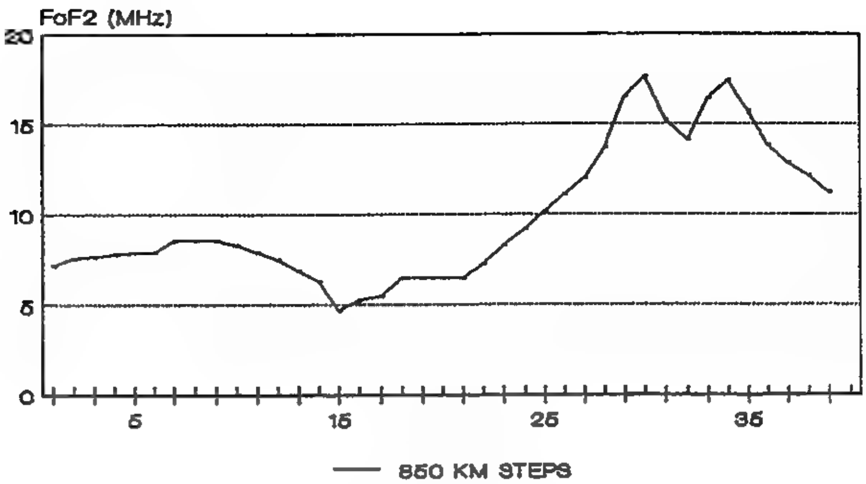


FIGURE 21. f_oF_2 variation along a great-circle path from Guemes Island, Washington, to Vadsö, Norway. NM7M to LA9EF, 1428 UTC, 10/26/91.

3.5 An Example of Extreme Long-Path Propagation

The most distant contact made, indeed verified, in this study was with Oistein, LA9EF, in Vadsö, Norway (70.15° N, 29.85° E); the date was October 26, 1991, and the time of contact was 1428 UTC. The LP great-circle distance from Guemes Island to Vadsö is 33,368 km, and the beam heading from Guemes Island is 191° east of north, very close to the gray line at the time. In its extremes in the southern hemisphere, the path reached 82.0° S geographic latitude and 86.2° S geomagnetic latitude.

Aside from those details, it is of interest to look at how the critical frequency of the ionosphere varied along the great-circle path and see where the equatorial anomaly became evident in the f_oF_2 variation and the actual magnitudes involved. Here it is more convenient to work with computer programs than with the volumes of f_oF_2 maps [*Leftin*, 1971]. In that regard, only two F layer algorithms in the amateur radio computer literature, MAXIMUF and FTZMUF2, are adequate to the task in the sense that they include the role of the geomagnetic field.

The MINIMUF program, widely used in amateur circles but known for its erratic MUF predictions, has an F layer algorithm which is essentially of solar origin, independent of the earth's magnetic field. When its algorithm is extracted from the program and used to create an f_oF_2 map, it produces a graphic display which has little resemblance to the map of a real ionosphere (see Figures 17–20 in this article) and is, at best, reminiscent of the early Chapman model of the F region cited in discussions of the reality of geomagnetic rather than solar control.

The MAXIMUF algorithm for the F layer was developed by *Raymond Fricker* [1985] and uses 26 mathematical functions to represent spatial, seasonal, and solar cycle variations of the F layer critical frequencies found in the CCIR *Atlas of Ionospheric Characteristics*. On the other hand, the FTZMUF2 algorithm was developed by *Damboldt and Suessmann* [1985] and makes direct use of the same database in the CCIR *Atlas* but involves interpolation methods to find the values appropriate for a given location.

Of the two F layer algorithms, MAXIMUF is the superior one, not only providing MUF predictions consistently closer to those from the IONCAP program but also giving remarkably detailed ionospheric maps (Murray, private communication) which compare quite favorably with critical frequency values found in the CCIR *Atlas* (Shallon, private communication). The FTZMUF2 program, while giving a good representation of the main ionospheric features in both respects, suffers somewhat from the limited detail that can be obtained by interpolation of critical frequency values in its database.

With those explanatory remarks, consider the case of the ELP contact with Vadsö, Norway. The variation of F region critical frequency along the great-circle was obtained by dividing it into 40 segments of about 850 km each and then calculating the value of f_oF_2 at each of those geographic locations using the MAXIMUF algorithm. The results are shown in Figure 21. Here, it is seen that critical frequency varies somewhat in the

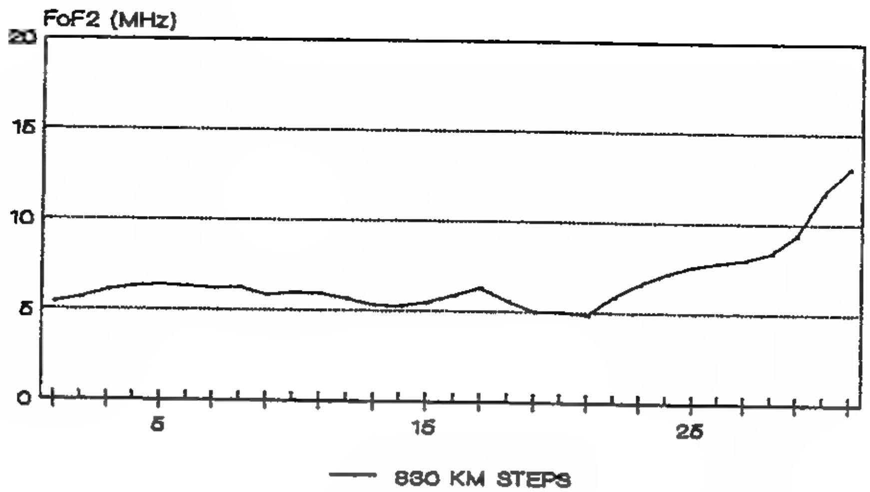


FIGURE 22. f_oF_2 variation along a great-circle path from Guemes Island, Washington, to Colombo, Sri Lanka. NM7M to 4S7CF, 1229 UTC, 6/24/91.

first half of the path, from 5 to 8 MHz, and then increases steadily after step 24 and goes through two peaks, 17.6 and 17.4 MHz, which are separated by a valley where the critical frequency is 14.1 MHz. (The same calculation, done slowly and in a tedious manner, was carried out using IONCAP and similar results were obtained, the rms deviation of f_oF_2 values of MAXIMUF from those of IONCAP amounting to 1.7 MHz.)

The geomagnetic dip equator is located close to the valley around step 32, and the two peaks in critical frequency represent the regions of peak electron density that are associated with the equatorial anomaly in the early evening hours. While this variation of critical frequency along the path clearly points to a strong horizontal gradient in the electron density, that quantity must be calculated in two dimensions, not just in the one that is direction along the path. When that is done, albeit in an approximate fashion, it does show that the gradient of the equatorial anomaly, as obtained by using MAXIMUF, was mainly along the direction of propagation.

The double peak in f_oF_2 on the approach to Vadsö points to a long chordal hop toward the final location on the path. As for the initial portion of the path, presumably that involved a conventional multi-hop mode between the earth and the ionosphere as no comparable gradient structure is found in Figure 21.

Of the other common paths in the present study, only the ones to Sri Lanka and India come close to the equatorial anomaly. In that regard, Figure 22 shows the f_oF_2 variation along a path to Sri Lanka. Here the critical frequency begins to rise significantly in the last 2–3 steps before the terminus. That variation probably affected the last downward refraction on the path but would not have given rise to a chordal hop, and, judging by the slow variation in critical frequency earlier, the other portions would have involved only earth-ionosphere reflections.

For the other categories of paths from this location, through the auroral zone or across the polar plateau, their final refraction region falls short of the evening portion of the equatorial anomaly. Further, the variations of f_oF_2 along the first portions of such paths result from sunrise or the crossing of the remnant of the equatorial anomaly off to the west, as seen in Figures 19 and 20.

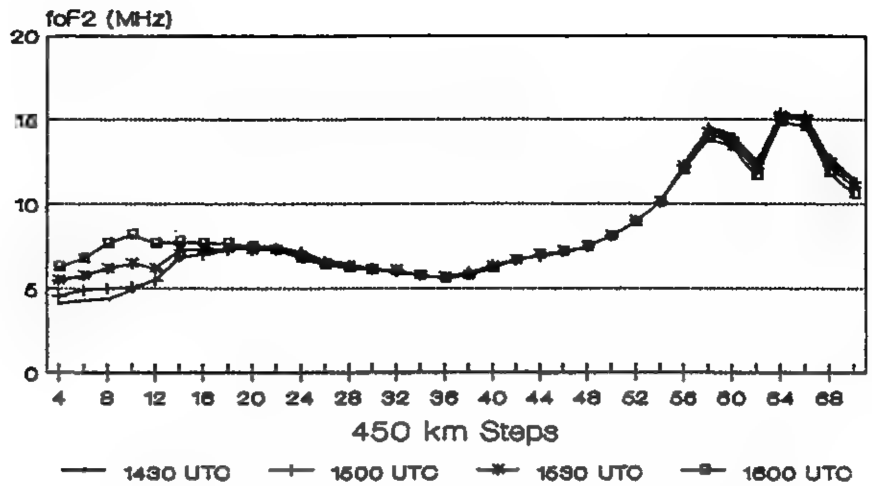


FIGURE 23. Sunrise variation of f_oF_2 values along a great-circle path from Guemes Island, Washington, to Switzerland in December.

3.6 More on the Gray Line

One cannot leave the above discussion about the equatorial anomaly without revisiting the matter of gray line DXing. This is the case as the method of following the variation of the critical frequencies along a path has direct application to that question. To illustrate the matter, consider LP DXing in the fall/winter season. Already, mention has been made of the fact that signals from the Indian Ocean area disappear after the paths become illuminated with the change of seasons. And the time-distribution of LP contacts has shifted to later times, as shown in Figure 1. So, going back to Figure 7, one would conclude that gray line considerations are important for DXing into Africa and Europe in December.

But what are "gray line considerations?" If you go to the literature, they are generally "static" in nature and involve the geometry of the terminator, something which changes regularly, year in and year out, but without any relation to solar activity. What appeal there is to matters which are ionospheric in character is only to the extent that D region absorption is minimal along the gray line. For my part, I would argue that gray line considerations are "dynamic" in nature, frequency-sensitive, and even localized to some extent rather than distributed *all* along a path. Let me give some examples.

Thus consider a path into Europe, say to HB-land in December. From Figure 7, you would think that D region absorption is the story. But if one looks at how critical frequencies change with time along the path, as shown in Figure 23, it becomes apparent that the opening really develops because of changes in the F region here along the West Coast. Thus, for success in the first refraction of 14 MHz signals heading toward Europe, a minimum critical frequency of about 5 MHz is needed in the F region at the apex of the first hop, around step 4 or 5 in the diagram. That develops as the sun rises out in the Pacific, about 1,400 km west of Los Angeles.

The ionization and critical frequencies along the rest of the path are more than adequate, and the path to HB-land opens after 1500 UTC. But that is a dynamic F region process, something which one can actually hear by following the enhancement of a signal for 10–15 minutes. The path closes more slowly as D region absorption changes, increasing more on the sunrise part of the path in the Pacific than it decreases on the part of the path which goes into darkness along East Africa and Europe.

Similar considerations apply for the path to South Africa, the main difference due to the fact that the path is shallower, going to 55° S as compared to 70° S latitude for the path to Europe. Thus opening and closing of the path are due to F and D region processes closer to the point of origin than in the other case.

Finally, one cannot conclude this discussion of the gray line without referring back to the original instance where it was brought up, the summer paths to India and Sri Lanka, as shown for June in Figure 6. There the paths appeared to be sheltered from solar illumination, but what makes them open? What makes them close?

To understand that, go to Figure 24, which shows the critical frequency variations along a path to India.

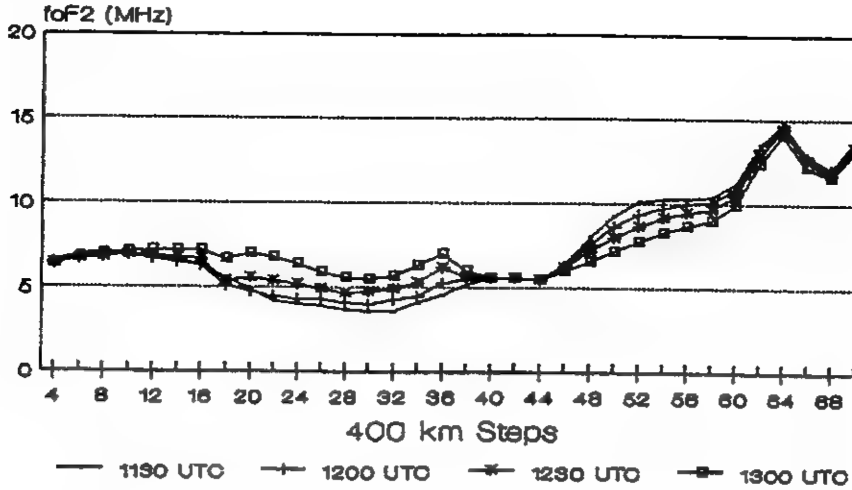


FIGURE 24. Sunrise variation of f_oF_2 values along a great-circle path from Guemes Island, Washington, to India in June.

Thus one can see that the opening to India develops because of a rise in the critical frequencies with sunrise along the path in the southern hemisphere, from about step 18 (13° S, 103° W) to the deepest winter part of the path at step 38 (76° S, 37° W). Again, the critical frequencies along the rest of the path are sufficient to support propagation, and, as expected, the path closes because of the growth of D region absorption on the western portion of the path where the sun is rising.

If you want to look deeper into the difference between the cases of propagation to HB-land and VU-land, refer back to Figures 19 and 20. The significant rise in critical frequency with sunrise in the northern Pacific area in December is because of the relatively long period of darkness after sunset (up to 16 hours at this latitude) and the decay of ionization at F region heights. For June, the long period of illumination during the northern Pacific area spring/summer season (up to 16 hours) means that less decay in ionization occurs there after sunset, and the F region variations important on the path to India are now found in the southern hemisphere, during its winter season.

Given these remarks, it should be clear that the earlier discussions of the gray line miss the essence of the matter in the present cases, the dawn enhancement of critical frequencies in the winter portion of the F region. This would apply also at higher frequencies, say on the 21 and 28 MHz bands. At lower frequencies where MUF considerations are less important, say 7 MHz, ionospheric absorption plays the greater role.

3.7 Simultaneous Short- and Long-Path Propagation

There are occasions in the morning hours around the equinoxes and during the fall/winter season when both short- and long-path propagation are in effect at the same time. How one notices those circumstances depends on the antenna systems in use. For example, I have noticed both SP and LP to be open when listening to a European station which used a dipole or a vertical antenna. Thus one hears multi-pathing from the two signals, but the details depend on how one's beam is oriented.

A case in point was ES1RA who uses "200 watts into a gp," and I've contacted him both SP and LP within 5 minutes. But when my beam was pointed north, his CW was muddled by the overlapping of the prompt SP signal and the delayed LP signal, a "trailing ghost." On that occasion, LP propagation was the better of the two, and when my beam was rotated to the south the effects of multi-pathing were not so severe. Moreover, since my QTH is on an island, a true low-noise site, I could even hear his weak SP signal first, a "leading ghost" coming in the back lobe of my beam, and then followed by the louder, delayed LP signal via the front lobe, now with a sharp, crisp termination on every dot and dash.

One also faces this same situation when the station at the other end was running a lot of power but using an antenna with a poor F/B ratio, typically a 2-element Quad. For an LP study like this one, this is particularly annoying as one has to spin the beam back and forth to be sure that when a given contact is

put in the log it is truly from a long-path direction. But with high power, multi-path effects can be quite pronounced, and one does not need a low-noise site to get a sense of what is going on. Thus, by listening carefully to the sound at the end of dots and dashes for a crisp termination, one can recognize when the multi-path effect is due to the early arrival of the short-path signals. This effect is most noticeable when there is a large difference between the short- and long-path distances, such as paths to and from Europe.

In spite of the discussion concentrating on leading and trailing ghost signals, one shouldn't think that the usual form of multi-path propagation doesn't exist on LP. Here, I am thinking of the strong "following echo" that arrives quickly due to the slight increase in slant path length on the next higher ionospheric mode with a higher radiation angle. However, the experience in this study would lead to the conclusion that it is rather uncommon in the case of LP propagation. Thus I've heard it only a handful of times and those were unusual in that the main signals were S9+, indeed some of the loudest LP signals I've ever heard!

One occasion of this sort of multi-pathing lasted about an hour and was quite evident on two strong signals, one station from Hungary (HA) and the other from Switzerland (HB). The HA signals were crisp, largely because the transmitter was keyed at a slow speed with a "bug." The HB call sign was familiar to me from previous LP contacts and the keying then was quite "soft" and heavily weighted. During the episode of multi-pathing, the HB signal was barely readable, just a loud blur or smear of CW here at 30,000 km distance. Myself, I have never liked that kind of keying and often wondered how it would sound when strong multi-pathing is in effect. Now I know, more like keyed door chimes than CW!

But I digress; back to the LP/SP problem. If local noise is too great a problem and does not permit the use of "ghosts," one must rely on signal strength variations with antenna rotation to establish the reality of an LP contact, or, if the other person speaks English, it can be confirmed by rotating both beams to SP. Indeed, such an occasion, when Peter, SM7BAU, and I spent some time checking both LP and SP propagation on April 1, 1991, was the actual stimulus that lead to the present study.

That was but the first of many times in the year-long study when two beams were used, sometimes showing only one mode to be open and other times that both modes were in effect. And, in the very last week of the study, it was repeated one final time at the suggestion of Jean, F8AH. Then, long-path propagation proved far superior and gave the same type of muddled, unreadable short-path CW mentioned earlier in connection with the ES1RA contact.

While time-consuming, that approach proves to be most interesting and can be explored frequently during the fall/winter season. Then one often notes that LP signals dominate early in an opening, but with the passage of time the reverse is true, and the opening finally closes when propagation is completely on SP and continues on that way for some hours.

Another interesting variation is shown by a contact I had with UZ3AYR in Moscow. On that occasion I called him and signed my call as NM7M/LP. He came back, saying "No, short-path," meaning he was copying my signals when his beam was pointing to the north. He went on to tell me to rotate my beam to the short-path orientation. I tried that but did not hear his signals. Then I switched back to the long-path orientation and explained that short-path was not open. I suggested he point his beam south but he became confused and the contact ended.

But later I heard his signals again, now much stronger. I called him again and he responded with "now long-path." All in all, it was clear to me that short-path propagation was not open at that time, and without knowing it he had conducted the first contact, transmitting and receiving, via the back lobe of his beam. That brings up the question of F/B ratios and LP DXing.

As I indicated earlier, I use a 3-element tri-band Yagi antenna. Being a compromise antenna, it is something of a "blunt instrument." Thus the forward lobe is rather wide, roughly 70° full-width between -3 dB power points. That is not unreasonable for such a modest antenna; indeed, if you consult the book *Yagi Antenna Design* by *Lawson* [1986], you will note that sort of beam width is found with some of the designs that he recommended.

The manufacturer of my tri-band antenna indicates that its F/B ratio on 20 meters is 20 dB. Not trusting numbers like that, I made my own checks using the transmissions from distant stations, e.g., W1AW at 3,900 km as well as European stations at about 7,500 km, as signal sources, and came up with a value of 18 ± 1 dB. Thus it is not out of the question to pick up a strong signal from the short-path direction via the back lobe of my antenna and confuse it for a long-path signal. Indeed, I have spent hours rotating my beam, back and forth, checking to be sure that I was not contaminating my log of LP contacts with signals from the SP direction.

3.8 Off Great-Circle Signals

In that connection, on one occasion just before the autumnal equinox I found signals from my antipodal friend, FT4WC, were weak in the usual direction, and, thinking of my earlier experience about back lobes, I swung the beam more to the west. Sure enough, his signals peaked about 35°farther to the west. But to be sure it was not due a side spur of the back lobe, I swung the beam farther north, looking to see how his signals were in the short-path direction. To my surprise, they were weaker in the SP direction, not what I had expected. I went back to double-check and found that the best signal came from about 35° westward from his usual position. So I had a real case of an "OGC" signal, one coming in from a direction which was off the great-circle path.

But that wasn't the end of it. My initial observations were made about an hour before dawn at this longitude. As dawn approached, the signals from FT4WC became stronger on his usual heading and by the time the sun was up, it was clear that his signal had swung around toward his usual long-path direction. Interesting! That was on September 19 and *Ap* was only 10.

By way of interpretation, that had to be an example of the influence of a transverse ionospheric tilt, primarily in the dawn sector. This can be seen from examination of the f_oF_2 map in Figure 17. There the iso-frequency contours around the location of this QTH (49° N, 123° W) are more indicative of a transverse ionospheric tilt for signals going to or from the south Pacific than the contours in the evening sector around the location of Crozet Island (46° S, 52° E).

There have been other occasions when off great-circle signals from LP were heard here but not more than 20 in the whole period, far less than one might expect from the remarks that surface in the literature from time to time. And there were other OGC signals heard during the study, but they were not LP signals. Here, I have I mind signals from the Indian Ocean area, say VU and 4S7, which are not heard via LP during winter months when their paths in the southern hemisphere are fully illuminated. Short-path can be open to that region in late December and early January, and on at least four occasions I made contacts into the area around the Arabian Sea, with N9NN/MM and AP/WA2WYR, as well as the Indian Ocean, with VU2KOJ and 4S7WP, when the geomagnetic field was relatively quiet.

Under normal circumstances their SP beam headings would be in the range 330–360° east of north, but on those occasions their signals came in 30–50° south of the SP headings. Again, this is to be interpreted as due to refraction of SP signals on encountering the strong ionospheric gradient in the dawn sector of the winter hemisphere (see Figure 20), the incoming signals being deviated toward the sunlit region.

While these observations are not large in number, statements in antenna books and other publications almost make one think that few, if any, of the LP signals come through on the great-circle directions. However, those comments always seem to lack any sort of statement as to the angular resolution of the antenna used in noting the direction, the operating frequency, date, time, or even a discussion of the propagation conditions when the OGC signals were encountered.

The 3-element tri-band Yagi used in this study on 20-meter CW had a beam width of about 70° between -3 dB power points. Of course, making a determination of a beam heading requires enough time, without QRM or QSB, to swing back and forth several times to make a firm judgment as to where the signal peaked in intensity. Thus any beam heading noted with my antenna has an uncertainty of ±35° associated with it, so any deviation from a great-circle bearing less than that amount is really not resolved to any degree of satisfaction.

If you have any doubt about that statement on the uncertainties in beam headings, try making repeated determinations of a signal's beam heading with your eyes closed or the dial of your beam direction indicator covered with opaque paper while looking at your S-meter. After several passes with the beam, recording each heading, I think you will understand what I mean.

A review of patterns of antennas with more than three elements [*Lawson*, 1986] indicates that the full width between -3 dB points falls to about 50° if the number of elements is increased from three to six. That represents a significant improvement, bringing the angular resolution down to about ±25°. Still that resolution leaves a lot to be desired when discussing the effects of ionospheric gradients.

The previous discussion dealt with results that could be obtained using the forward lobe of a beam antenna. There is another approach that is possible, using the null in the beam pattern roughly at right angles to the direction of the main lobe. That is not without difficulty, however. Just to list some of the problems, there is the matter of the depth of the null at the radiation angle of the incoming signals. While

the patterns shown in *Lawson* [1986] suggest greater resolution using the null method, it is well known that nulls are shallower at radiation angles other than zero, as with free-space antenna patterns. Thus some of the sharpness of the null would be lost.

Another problem has to do with noise, attempting to null a signal in the face of a noise background. Again, with noise the null in the pattern is shallower than in its absence. And, if one uses an S-meter in determining beam headings, there is the matter of threshold sensitivity of the AGC circuit and its time-constant, especially when working at low signal levels.

In contrast to the approach using the front lobe, where one gains in angular resolution by using more than three elements, the side null of beam antennas becomes wider and more complex on going to more than three elements. Indeed, side lobes can develop in the forward direction, perhaps confusing the situation rather than clarifying it with the null method.

Tri-banders, being compromise antennas. may not even measure up to the patterns of mono-banders given by *Lawson* [1986]). It is clear that they would perform closer to theoretical calculations if operated on 10 meters, where antenna currents are concentrated in the center portions of the elements, closer to the correct length for the band. It would be helpful if antenna manufacturers would give realistic data on their products, band by band, but that's probably asking for more than they are willing to come forth with. So without them all we can do is cite the main features of an antenna system in giving an OGC observation as well as the band, date, time, geophysical conditions.

With accurate reporting in the future perhaps we can pin down just what is going on with OGC signal reports in amateur circles. But, while on the topic of OGC signals, it might be worthwhile to touch on some of the scientific results as they are often referred to in amateur radio publications, perhaps out of context at least with regard to LP propagation on the HF bands. Here I refer to the work of the Max Planck Institute of Aeronomy in Lindau, Germany. This was described in some detail in the March 1975 issue of *CQ DL* by the former Director of the Institute, Dr. Walter Dieminger, DL6DS, and in other publications by Dr. Jurgen Röttger, DJ3KR [*Röttger*, 1976].

The German work started during the IGY in 1957 and continued until about 1975. One of the main interests was an unusual feature of signal propagation through the nighttime F region at low latitudes, so-called rapid- or flutter-fading. This type of fading is attributed to the scattering of waves by irregular columns of ionization ("spread F") which rise well above normal F region heights. Such structures set in after sunset near the geomagnetic equator and generally move from west to east with speeds of 100–300 meters/second. Signals which pass through them show fading and distortion to such an extent that the Germans have been known to remark that "Beethoven sounds like jazz" when in effect during overseas broadcasts from Germany to Africa.

The German research involved signal transmissions on a 7,900 km path from Lindau, Germany, to Tsumeb, Namibia, in southern Africa, and showed that the signals received at Tsumeb via $3F$, $4F$ and $5F$ propagation modes often involved significant deviations from great-circle directions. Indeed, they reported deviations up to 50° either side of the great-circle line of propagation. but these were found mainly in the evening hours (1700–2300 UTC) and during times around the equinoxes. By way of illustration, an occurrence frequency distribution of OGC observations on 18 MHz was given in 10° steps and had an rms deviation of 20° from the central direction.

The angular deviations were observed using an ionospheric trans-horizon radar, and a resolution of about 10° was obtained from a rotating transmitter antenna with stacked 3-element vertical Yagi antennas which were fed 180° out of phase. That feed system produced a deep minimum in the horizontal radiation pattern in the forward direction of the antenna. The transmissions, their direction relative to Tsumeb, and reception were then coordinated in time. Thus, for a given beam direction, when signals were received in Namibia the scope trace of the signal strength showed the deep null, and its position in time was used to determine the extent of the deviation from the original great-circle path direction.

The earlier remark about OGC work perhaps being taken out of context in discussions of LP propagation essentially refers to the fact that the German research dealt with off-great-circle propagation from the side-reflection area of spread-F irregularities. And that was on high-angle, multi-hop modes which occur after local sunset. For the LP case, that many additional earth-ionosphere hops across Africa would surely reduce signal strengths to the point where LP contacts into Europe would be impossible, as noted earlier.

But that is not to say that the spread-F irregularities are not relevant to the amateur radio community as they can give rise to scattering of VHF signals comparable to auroral back-scatter. However, in contrast to

the auroral case where scattering is from extended, field-aligned irregularities in ionization near the vertical direction, the equatorial spread-F irregularities at high altitudes extend horizontally along the geomagnetic field and cause forward scattering, carrying VHF signals to great distances.

To conclude this discussion, it should be noted that in the present study the auroral zone and polar paths from the Northwest fell short of the equatorial anomaly, and the only paths that might be even remotely connected with the German work are those extreme polar paths going into Europe. Even at that, LP connections being a dawn-dusk affair, they would only touch marginally on those times and the propagation conditions which continue well beyond sunset over Africa.

Most often at this end the only unusual features of ELP signals that were noted had to do with "ghosts," leading or trailing, or occasional multi-pathing from higher propagation modes. Only once, when listening to an unintelligible blur of high-speed CW, did the idea of flutter fading ever cross my mind. More than likely it was nothing but multi-path echoes.

PART 4

4.1 Discussion of Factors Affecting LP Propagation

In discussing LP propagation, the first matters that should be dealt with are the facts that LP propagation is in effect on almost 100% of the days when the earth's magnetic field is without disturbance and for hours at a time. Now, in a sense, LP propagation amounts to a shorter version of around-the-world (RTW) propagation, and for a study of that we can turn to an article by *Hess* [1948] which summarizes the German studies of RTW echoes during WW-II. That study showed similar results for the occurrence and duration of "circulating signals."

In ionospheric terms, the presence of RTW signals means that the conditions for propagation are fulfilled at refraction points on a path around the earth's circumference, a distance of 40,000 km. The telling fact of the observations is that the conditions persisted for hours, not being just something like the momentary *green flash* found with the first or last part of the sun's image at sunrise or sunset on a clear day. Now the green flash is the result of a refraction phenomena and the same is true of RTW propagation. There is a vital difference, however, as the green flash involves the effects of sunrise or sunset on the neutral atmosphere while RTW echoes involve the effects on the F region of the ionosphere.

Now RTW signals on a given frequency propagate along great-circle paths for two simple reasons: 1) the level of ionization required for F region refraction is being created by photo-ionization along the sunrise portion of the terminator, and 2) the lingering daytime levels of F region ionization along the sunset portion of the terminator decay slowly by electron-positive ion recombination. While long-paths are shorter than 40,000 km, the same line of argument can be made for those cases where the desired propagation path lies close to the terminator or gray line.

In essence, the ionization conditions for LP propagation are created along and continue to exist well behind the terminator as it moves from east to west. Put another way, like a boat the moving terminator leaves a wake or a wave behind it as it goes across the sky, a crest of rapidly increasing ionization with sunrise on the morning side and a trough of slowly decreasing ionization with sunset on the evening side. Of course, at lower altitudes along the exposed portion of the great-circle path D region absorption starts to increase with sunrise while the absorption decreases on the dusk side as it moves into darkness.

Were it not for the increasing absorption of signals on the sunlit portion of the path, LP propagation would continue much longer, until the decay of ionization somewhere along the dusk portion reached a level which no longer supports ionospheric refraction. As it is, however, D region absorption dominates and ultimately closes the path for the day; the path then reopens when the required levels of ionization are "refreshed" at the next sunrise, about the same time on the following day.

As noted earlier in connection with LP propagation into Africa during the recent spring/summer season, gray line conditions are not always required for LP connections. In those circumstances two things were of importance: 1) the fact that the observations were made near the peak of Cycle 22, and, again, 2) ionization in the F region decays slowly with the onset of darkness. The first point means that critical frequencies in the F region were quite high during daytime hours, and the second helped to maintain the critical frequencies at sufficiently high values to support propagation when portions of the path went into darkness. But with the decline in solar activity as Cycle 22 progresses, the first condition will not continue indefinitely, and at some point LP propagation into Africa on 14 MHz during the summer/spring season will begin to falter.

Having made the point that LP propagation is really *the rule*, not requiring any sort of ionospheric circumstances beyond the rising and setting of the sun, we should next deal with the exceptions, unusual solar/terrestrial circumstances which may disrupt LP propagation. This is necessary as the ionosphere is not just the ionized portions of a spherical distribution of terrestrial gases exposed to solar UV radiation. Indeed, it is permeated by the geomagnetic field which adds a unique spatial structure to it, in both latitude

and longitude.

Thus the geomagnetic field will influence the solar particles which reach the earth's orbit, even serve to transmit some of them directly down into the lower ionosphere where they can increase ionization or, indirectly, through electric and magnetic field variations, produce effects which may reduce the level of ionization created by solar UV radiation. Thus the types of possible disturbances should be the next topic in this discussion.

4.1.1 Polar Cap Absorption Events

Having said that, we begin at the high energy end of the spectrum, as it were, considering polar cap absorption events due to energetic solar protons. As is well known, those particles are accelerated to tens and hundreds of MeV energy during some solar flares and sent out into the interplanetary magnetic field, some finally reaching our polar ionosphere.

The ideas and understanding of PCA events that apply to short-path propagation also apply to the long-path case. But it is important to note that the particle influx into the two polar regions may not be the same, depending on how the particles gain access to a particular polar cap. Thus solar protons can enter directly at the front of the magnetosphere, or indirectly, reaching the polar cap via the magnetotail behind the earth where auroral processes occur. And access varies according to season as one polar cap may be more inclined toward the advancing solar protons than the other.

Also, there may be differences in conditions on signal paths in the two hemispheres, namely the amount of sunlight they receive. That has an effect on the *D* region absorption on the paths, greater absorption by as much as 5–10 times being found in the sunlit polar cap during a PCA event. A case which involves both of the last two points comes from the PCA event in June '91. Then, an ionospheric absorption instrument at Thule, Greenland, recorded 17 dB of absorption on 30 MHz at 1420 UTC on June 11, 1991, while a similar instrument at the Amundsen-Scott Base (South Pole) recorded only 1.5 dB of absorption. At the time, Thule was in full sunlight while the South Pole was in darkness. But without particle flux data, say from detectors on a polar orbiting satellite, it is impossible to interpret the differences in those observations any further.

4.1.2 Auroral Absorption Events

Proceeding down the energy scale, but still in the disturbance regime, we come to auroral absorption events due to energetic electrons, now accelerated to tens and even hundreds of keV of energy by processes within the earth's magnetosphere. Those particles are known mainly for the optical emissions they produce in the nighttime hours, but because of their high fluxes they can also create significant ionization, now at *E* layer heights, and may give rise to ionospheric absorption of radio signals passing through the regions.

While both PCA and AA events are sporadic rather than regular in occurrence, they differ in details of frequency of occurrence, duration, and times of incidence. Thus solar protons can produce PCA events of long duration, even lasting for several days, after some large solar flares, but auroral electrons produce AA events more often and with durations measured in hours. And instead of being slowly varying and continuous as with PCA events, AA events generally show rapid time-variations in absorption, say in hours or less, and most often are limited to certain times of day. Moreover, PCA events extend broadly over the two polar caps while AA events are quite limited in latitude and longitude in the auroral zones.

4.1.3 Long-Path Propagation and Auroral Disturbances

In connection with LP study, it is necessary to look in some detail as to how AA events develop, particularly with regard to their temporal and spatial relationship to the auroral zone as a whole. So, to proceed, one must first note that AA events occur mainly around local (magnetic) midnight when auroral forms become active, and involve only modest ionospheric absorption. For example, typical AA events at those times produce up to 1–2 dB absorption of cosmic radio noise on 30 MHz and are accompanied by ionospheric current systems (auroral electrojets) which reduce the horizontal component of the earth's magnetic field by a few hundred nanoteslas in the vicinity of the aurora.

It should be noted there is a degree of geomagnetic conjugacy [*Brown*, 1966] here, AA events and electrojet currents in one hemisphere being accompanied simultaneously by effects of similar magnitude at comparable

geomagnetic latitudes and longitudes in the other hemisphere. Another important aspect of AA events is that, since they involve ionization in the *E* region, they do not show a day/night ratio [*Brown*, 1966] in absorption like PCA events [*Reid*, 1987] in the lower *D* region. Thus auroral effects could be similar in magnitude in the two hemispheres, no matter how daylight differs between them.

The present study of LP propagation was carried out largely in the time interval between 1200 and 1500 UTC, and for that purpose it is necessary to determine whether the signal paths through southern auroral latitudes passed close to sites of auroral activity at those times. For simplicity, consider the starting time of a typical spring/summer LP session, 1200 UTC. At that time the sub-solar point is located at 0° east longitude, and, if geomagnetic conditions were other than absolutely quiet, one might expect some modest activity at auroral zone latitudes in both hemispheres and the midnight sector of local time, around 180° east longitude [*Newton*, 1991].

Now it is of interest to find whether the great-circle paths discussed earlier come close to regions of auroral activity at 1200 UTC. In that connection, it is a straightforward calculation to determine the longitudes of the most southerly excursions of the auroral zone paths listed in Table 2. For those paths toward the sunlit hemisphere, to India and Sri Lanka, the most southerly excursions in geomagnetic latitude are reached at geographic longitudes of 12° and 24° east, respectively. Further, for other paths into the dark hemisphere, toward Capetown on one extreme and Swaziland on the other, the most southerly excursions in geomagnetic latitude of the auroral zone paths are reached between 89° and 109° east geographic longitude.

Thus we see that the great-circle paths to Sri Lanka and India pass through auroral zone latitudes in the hours from late morning to noon local time, well away from the regions of auroral activity . In contrast to that situation, the other auroral zone paths have their most southerly excursion in geomagnetic latitude at geographic longitudes which would place them in the auroral latitudes at local times from sunset into early evening. Thus at 1200 UTC both groups of paths are well away from auroral activity and ionospheric absorption in the midnight sector.

Given that information, it becomes clear that the paths in Tables 2 and 3 are out of harm's way as far as times of minor to modest auroral activity. But with more intense auroral activity, say during those geomagnetic storms which produce strong auroral currents able to decrease the horizontal component of the local field by up to 1,000 nanoteslas or more, auroral absorption of more than 4 dB at 30 MHz would be expected for signals passing through the auroral *E* region.

But the longitudinal extent of regions of ionospheric absorption increases during those times, moving both toward earlier hours of the evening and the region around the dawn meridian. Indeed, slowly varying, intense absorption (SVIA) events may occur in the dawn sector with ionospheric absorption reaching values more than 6 dB on 30 MHz.

On that basis, the great-circle paths to the sites in Table 2 would be fairly immune from auroral absorption around 1200 UTC, but for later times, more toward 1500 UTC, the sun would move westward and the center of auroral activity in both hemispheres would move closer to where the westward paths into the dark hemisphere pass through the auroral zone. That would increase the chances that absorption effects would affect LP propagation during more intense geomagnetic storms.

As for the polar paths in Table 3, they cross through the auroral zone twice. For paths toward the dark hemisphere (to 9J2, ZE, and 7Q7), the crossing into the auroral zone is closer to the region of auroral activity around 180° east longitude than where it emerges from the polar cap and crosses the auroral zone again on going toward the terminus involved. Thus auroral activity could affect LP propagation by absorption processes in that particular region.

The other paths in Table 3 go deep into the southern polar cap and follow steep trajectories, entering the auroral zone around 122–164° west longitude and emerge around 50–60° east longitude. In essence, they would be fairly immune to effects from auroral absorption.

4.1.4 Other Effects from Auroral Activity

Beyond absorption effects, there are other ways by which auroral activity may affect HF propagation. Thus *Davies and Rush* [1985] as well as *McNamara* [1985] point out the importance of an *F* region or mid-latitude trough, a region of low electron density that is just equatorward of the auroral zone, extending magnetically east and west during the nighttime hours. The region displays a steep gradient in electron density (or critical frequencies), and, like the lower boundary of the auroral zone, it is quite variable in location during

active periods. Indeed, the spatial and temporal resolutions of the earlier ionospheric sounding programs were generally insufficient to display the features of the trough, and its presence, being quite variable, is not shown in any of the usual f_oF_2 maps.

McNamara [1985] has argued that the sharp gradients in electron density at the walls of the mid-latitude trough may result in reflections and off-great-circle propagation. In that connection, it is of interest to note that *G. Ivanov-Kholodny* [1990] has cited such reflections for the 12.944 MHz transmissions of the New Zealand broadcast station ZLP. Thus the observations at Kharkov in the USSR showed the presence of both SP and LP signals from ZLP but, in addition, their directive antennas picked up signals reflected off the northern and southern auroral troughs or canyons (sic). It should be noted, however, that those transmissions from an overseas broadcast transmitter involved tens of kilowatts of radiated power, well beyond the usual range of amateur radio transmitters, and thus are more relevant to the so-called "operational MUF" than the MUF's calculated from ionospheric refraction that are applicable to the amateur experience.

But in spite of that caveat, more important to the present study is that none of the paths given in Tables 2 and 3 came in close contact with the regions of more intense auroral activity, and thus those considerations are of no concern to the present observational material. This is supported qualitatively by the fact that long-path signals heard during the time interval 1200–1500 UTC have a steady quality about them.

That is in sharp contrast with short-path signals from Europe to the West Coast which pass through regions of auroral activity in Canada and Greenland during times close to local (magnetic) midnight. At those times, the refraction of signals may be influenced by any rapidly varying regions of ionization they pass through, say in the vicinity of active aurora displays, and acquire an eerie, hollow sound that must be heard to be appreciated. But, again, nothing like that is heard in the morning hours with LP propagation, at least in my experience, and thus points to LP paths from 1200 to 1500 UTC being well away from active auroral regions.

4.1.5 Magnetic Storm Disturbances

Electrons and protons with energies well below those of PCA solar protons and auroral electrons are also able to influence, indeed disrupt, HF radio propagation. These particles, called solar plasma, originate on the sun and affect the shape and dynamics of the geomagnetic field for a day or two during geomagnetic storms.

Geomagnetic storms begin either suddenly or gradually, the horizontal and vertical components (H, D, Z or X, Y, Z) of the geomagnetic field then departing significantly from their typical daily variations. Storms with a sudden commencement (SC) originate with solar flares and bursts of plasma which leave the vicinity of the flare site, sometimes arriving at the outer reaches of the earth's field anywhere from 20 to 40 hours after the flare.

Storms of gradual commencement (GC) show the same sort of geomagnetic variations, the main difference being that the degree of the disturbance and the abrupt impact of a solar plasma shock front is lacking. Instead, gradual commencement storms are attributed to fairly steady streams of solar plasma which sweep past the earth as the sun rotates. The source regions for the gradual commencement storms are termed *coronal holes,* regions in the solar corona where solar field lines connect with the interplanetary field, and thus allow the escape of solar plasma which may then impinge on the earth. These regions may be of long duration and thus give rise to geomagnetic activity with a recurrence tendency related to the 27-day period of solar rotation.

The main effect of geomagnetic storms on the HF bands is the lowering of the maximum usable frequency (MUF) on paths of interest. This results from a reduction of the electron density at F region heights; however, as a geomagnetic storm wanes, the critical frequencies of the F region return to their normal values, and HF propagation is gradually restored to its pre-storm condition.

These effects are the greatest at high latitudes. In the case of the present study, the F region ionization in the southern hemisphere is on the feet of geomagnetic field lines which go out 6–7 earth radii before returning to the northern hemisphere. Those field lines pass closest to the magnetopause and have the greatest exposure to electrodynamic processes which result from the impact of solar plasma. But those effects may propagate even deeper into the magnetosphere during major magnetic storms and result in lowering the critical frequencies on field lines at lower latitudes. In such cases, propagation fails on most paths of any length. But with time, electron densities begin to increase again and paths are restored.

In the present study of LP propagation, the presence of a magnetic storm would reveal itself by the band being dead at the start of an LP session, no signals heard in the pre-dawn hours from low-latitude stations out in the Pacific Ocean area. If the storm was of major proportions, say induced by flare outbursts as in June and July '91, that situation would continue throughout the first and possibly the second and third LP sessions, and the sessions would prove barren with regard to LP contacts.

But if the storm were minor, as is more typical of those due to coronal holes, or in a recovery phase at the time of an LP session, propagation would begin to return with sunrise at F region heights on regions in the nearby area. Thus the nocturnal ionization levels to the west would begin to recover from their depleted condition by the incidence of solar ultraviolet radiation. That restoration of the electron density in the ionosphere would serve to produce the final refraction of signals necessary to complete LP links to this location, particularly from Europe and Africa.

That last point is shown most clearly after the autumnal equinox when solar illumination is increasing in the southern hemisphere. Then, an LP session during the recovery phase of a magnetic storm is striking because of the dominance of signals from Europe and the near absence of signals from the Pacific Ocean area, say VK's and ZL's. The reason, of course, is that around 1200–1500 UTC the ionosphere over Europe is well illuminated while it is still dark out in the Pacific. Then LP propagation is possible via polar paths through the Antarctic F region when ionization is restored by sunrise on the F region of the west coast of the USA. The next day, VK's and ZL's return to the pre-dawn hours after the low-latitude F region has been restored by a full day's exposure to solar ultraviolet radiation, starting with the next sunrise.

4.1.6 Ionospheric Modes in Long-Path Propagation

Now, having dealt with the most frequent or common forms of disruption of LP propagation, we should turn to "the rule," LP propagation itself during quiet times, either magnetically or ionospherically. The statistics presented earlier indicate that nothing unusual is required to send radio signals more than half-way around the earth. As a matter of fact, LP paths covering three-quarters of the earth's circumference, say more than 30,000 km, are not out of the ordinary on any quiet day. Of course, there would seem to be a minimum amount of ionization required in the ionosphere for such connections to be possible.

Now, if you're an astute observer of the propagation scene, you probably would have felt somewhat uncomfortable at that last statement, "a minimum amount of ionization," and you began to wonder how I was going to finish or qualify that last statement. Your concern might be related to the lack of mention of propagation by chordal hops or whispering gallery effects, situations requiring less than normal ionization for successful propagation because of a low angle of incidence on the ionosphere. Another matter would be propagation across the equatorial anomaly, mentioned earlier in this report. And you would be right as "a minimum amount" of ionization is probably not the right way to speak in connection with those aspects, possible or otherwise, of LP propagation.

So let's turn our attention to those modes and how they would be related in LP propagation. For a beginning, chordal hops or the whispering gallery mode are thought to involve consecutive wave reflections off the ionosphere without the adverse effects of D region absorption and ground losses associated with intermediate earth reflections. The chordal hop is the fundamental unit in such discussions, and the whispering gallery mode is obtained from a series of shorter chordal hops. But, in the last analysis, for successful communication any ray path must start and end with a multi-hop type of refraction that touches the earth's surface.

4.1.7 Chordal Hops

Apparently the idea of chordal hops began with a suggestion by *Albrecht* [1957]. The problem was that the strength of LP signals from Europe to Australia was just too great, inconsistent with the calculated losses expected from intermediate ground reflections and ionospheric absorption in the usual earth-ionosphere hop mode. That may have been a good suggestion but for the wrong reasons, as the relation for field strength and distance in use at the time proved to be less than satisfactory. In any event, in order to have chordal hops, ionospheric tilts were required. Such tilts or gradients in electron density were known at the time, found in the f_oF_2 maps used to predict MUF's for HF propagation. Examples of tilts or gradients were discussed earlier.

Later, *Hortenbach and Rogler* [1979] expanded the discussion by showing that the discrepancy between predicted and observed values of signal strength was 25 dB on the LP connection between Wertachtal, Germany, and Melbourne, Australia, a path similar to that considered by *Albrecht* [1957]. Their suggestion was that the discrepancy could be resolved by two considerations, introducing an antipodal focusing gain of electromagnetic waves between concentric spherical surfaces, the ionosphere and the earth, and a reduction of signal losses due to tilt-supported propagation.

In reaching that result, *Hortenbach and Rogler* [1979] tempered the theoretical predictions of geometrical optics for the antipodal focusing of light, suggesting that the infinite gain at the antipodal point be limited to 30 dB. At the distance of Melbourne, some 4,000 km beyond the antipode of Wertachtal, that gave the 16 dB cited above.

The idea of focusing gain is not new, being essentially a result of the fact that the ionosphere is concave, much like a mirror. And there is geometrical defocusing as well, at ground reflections from the earth's convex surface. Further, the ionosphere is not perfectly smooth nor is the earth's surface, both resulting in losses by scattering of electromagnetic waves. Added to that is the fact that there are great geographical variations in ionospheric conditions, say height and spatial gradients. Those last considerations were cited by *Davies* [1965, 1990] as reasons to doubt that antipodal focusing would be of any great importance.

Another aspect of propagation to antipodal distances and beyond is guided propagation in the ionosphere, something that can occur along paths when the critical frequencies of the ionosphere are too low to support the usual multi-hop mode. Observations on that mode were presented by *Bold* [1972] and dealt with pre-sunrise increases in signal strength observed at an antipodal region. In this instance the transmitter was at Tangier, Morocco, and the receiver at Ardmore, New Zealand, and it was argued that the critical frequencies between the two were too low to support normal multi-hop propagation. Thus the increase in signal strength was attributed to tilt-induced termination of propagation above the MUF from chordal hops which originated near the transmitter site. A summary of this and other types of propagation without any sort of intermediate ground reflection can be found in CCIR Report 250-6 [1986].

Now, having given a brief account of the various proposals, the question arises as to just how those ideas might apply to the present study. For example, as noted earlier, Crozet Island (FT4WC) is close to being antipodal to my QTH, and the paths from here to the Republic of South Africa (ZS) are in the range around 23,500 km, roughly the same distance as the path treated by *Hortenbach and Rogler* [1979]. Whatever the antipodal and distance considerations, there is a difference in the two cases: the paths from here to South Africa all pass through the auroral zone, 60–70° S geomagnetic latitude in the southern polar regions, while the case treated by *Hortenbach and Rogler* [1979] only reached the mid-latitudes, 51° S geomagnetic latitude to the east of New Zealand.

So can we locate the position for the chordal hop(s) in a way that is consistent with both cases? Can chordal hop and multi-hop paths exist simultaneously? Or do we have to invoke chordal hops on a case by case basis? Before getting to those points, however, we need to consider the role of the equatorial anomaly in HF propagation. Then, we can go back for an over-view and try to bring observations and theoretical ideas together in a consistent fashion.

4.1.8 The Equatorial Anomaly

As indicated earlier, the equatorial anomaly of the ionosphere is two parts of the F region, having higher than normal electron densities as well as heights, which are located about 15° on either side of the magnetic dip equator. Those regions are most notable during daytime hours, reaching the extreme values around early evening. Propagation of HF waves through that kind of region has been discussed by *Davies* [1965], including the feature of chordal hops which gives two ionospheric reflections without losses due to an intermediate ground reflection. In addition, ray tracing for HF waves going through the region show that it may also involve some focusing gain, the energy radiated from the transmitter being concentrated in a small region of a few hundred kilometers extent.

In the language of ionospheric physics, the two portions of the equatorial anomaly provide examples of ionospheric tilts or gradients, and the parts of the anomaly in the evening sector probably have the greatest electron density gradients in the undisturbed ionosphere. Other examples of strong density gradients are found around sunrise in the winter part of the ionosphere and, to a lesser extent, around sunset . But those are single electron density gradients, not a closely spaced pair as found near the geomagnetic dip equator.

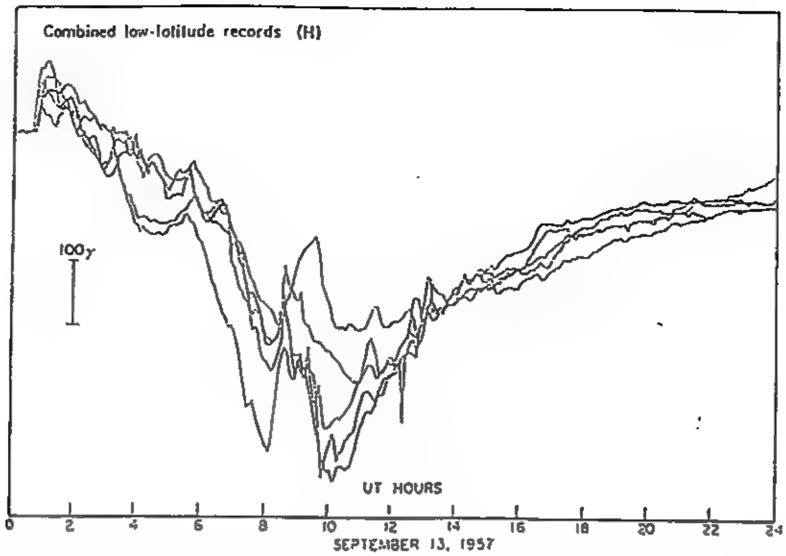


FIGURE 25. Horizontal component variations of the earth's field at low latitudes during the magnetic storm of September 13, 1957. (Note: 100 γ = 100 nT.) From *Menvielle and Berthelier* [1991].

But, in any event, whatever the gradient, it will have the greatest effect on the forward propagation of HF radio waves if the waves approach the gradient in the direction of most rapid spatial variation of the electron density.

The ionization in the equatorial anomaly is created, of course, by solar ultraviolet light, and will vary with solar activity in the short-term and with the sunspot cycle in the long-term. Thus, for a given month and time of day, the critical frequencies in the anomaly will differ with sunspot numbers, as may be seen by examining the f_oF_2 maps in the three-volume series *Ionospheric Predictions* [*Leftin*, 1971].

Before leaving the equatorial anomaly and going to the more general problem of reconciling aspects of LP propagation with the various theoretical ideas, we should add a few words about the history and origin of the anomaly. Thus, we first have to note that it was recognized in ionospheric records back in the late '40s, being most pronounced around sunset, and has been shown in f_oF_2 ionospheric maps ever since that time. In amateur radio circles it is credited for trans-equatorial propagation (TEP) at frequencies higher than conventional MUF calculations would predict.

As for its origin, ideas have developed in the course of time, but at the moment it would appear that the origin involves the diffusion of ionization away from the geomagnetic equator due to the combined influence of an eastward electric field E at equatorial latitudes and the northward, horizontal magnetic field B. Thus the ionization due to solar UV drifts upward, something like a "fountain effect," due to the effect of the perpendicular E and B fields, and then diffuses away from the geomagnetic equator. And it should be noted that the origin of this effect is considered to be the same as that which gives the quiet solar variation Sq of the geomagnetic field near the dip equator.

In addition to the quiet solar variation Sq mentioned above, the earth's magnetic field will also show storm variations at low latitudes. Thus, with flare-induced storms, the sequence of events starts with the storm sudden commencement (SSC), the earth's field showing a sudden change, say tens of nanoteslas either positive or negative, all around the globe in a minute or so. That is followed by what is called the positive phase, the magnetic field at low-latitudes being raised above normal values due to compression of the geomagnetic field by the arrival of the solar plasma. That may last for several hours, and then comes the main phase, the earth's field dropping below normal values.

This sequence of events is illustrated in Figure 25 (from *Menvielle and Berthelier* [1991]), showing variations of the horizontal component of the field at five low-latitude stations. These low-latitude variations of the earth's field are due to the augmentation of the ring current, a current system which is carried by energetic protons at a geocentric distance of about 3 earth radii.

In viewing magnetic records as in Figure 25, it is helpful to use the notion of "storm time," reckoned

from the time of the storm sudden commencement. That proves valuable not just in describing low latitude magnetic variations but also in connection with HF propagation as F_2 maximum electron densities, related to critical frequencies, have been analyzed in a similar fashion. Thus, for strong geomagnetic storms, say like those in June and July '91, *Matsushita* [1959] found that the maximum electron densities at equatorial latitudes decreased by about 10% during the first few hours of storm time; later, the electron densities recovered and even showed a modest increase above pre-storm values.

As shown by Figure 9.22 in *Davies* [1990], at geomagnetic latitudes of 30° and above, maximum electron densities fell by 10–30% during strong storms and, of course, resulted in large decreases in critical frequencies (and MUF's) and major disruptions of propagation. The statistical pattern found by *Matsushita* [1959] suggests near-recovery after about 72 hours of storm time. For weaker storms, like those associated with gradual commencements due to coronal holes, the storm time variation of maximum electron densities is less dramatic, and individual storms may depart significantly from the average behavior in storm time. But, in any event, MUF problems result when the electron densities drop below their normal values.

4.1.9 The Winter Anomaly and Stratwarms

At this point, we've considered the various forms of disturbance that can affect LP propagation as well as the factors which contribute to its success. There is still one more disturbance or effect that we need to consider, not so much for its reality as its mythical proportions. Here, I am talking of the *winter anomaly* in D region absorption and its purported relation to increases in ionospheric absorption with stratospheric warming, *stratwarms* for short. So let's review the topic and see how it bears on the present study of LP propagation.

All the earlier types of disturbance result directly from the interaction of particles and fields, i.e., plasma, particles, or photons of solar origin interacting with the geomagnetic field, and affecting the ionization in the D, E, and F regions. Those disturbances have time-scales as short as minutes (bursts of solar X rays and auroral electrons) to hours and days (polar cap absorption events and magnetic storms) and are routinely detected by satellites and ground-based instruments. But there is another possible effect or disturbance, one related to the neutral atmosphere, which increases signal absorption over a wide range of latitudes and longitudes by a coupling between the stratosphere and the D region.

This has been observed to have a long time-scale by monitoring radio signals in the medium frequency range (0.3–3.0 MHz), the *sporadic winter anomaly* with days or groups of days when the absorption is high even though the sun is at a large angle from the zenith. Along with that is the more regular winter anomaly which involves smooth increases and decreases in absorption on a seasonal time-scale. Both play a role in radio propagation.

Those effects were established in the last 50 years or so and are summarized in the recent paper by *Garcia et al.* [1987]. Of the two, the sporadic events are of more interest in that they are of shorter duration and might add to or stand apart from the ionospheric disturbances already cited above. Indeed, at present there are some who equate the Stratwarm Alert broadcast on WWV at times in winter with possible large, disruptive increases in absorption of HF signals. In that regard, a brief discussion of the current theoretical understanding of the regular and sporadic anomaly would be in order. Then, one can see if HF propagation on both short- and long-paths might be affected by stratwarm conditions,

For any increase in ionospheric absorption to occur, there must be an increase in the electron density in the D or E regions. If the flux of solar UV radiation does not change, sources from within the ionosphere have to be considered: reductions in the rate of electron-positive ion recombination due to temperature changes and/or increases in the number of target molecules exposed to the solar UV flux. In that last category, the principal targets are molecular oxygen, known to be a major constituent at D region heights, and nitric oxide, NO, a minor constituent and one that is variable, even capable of being increased by atmospheric transport.

The current understanding of these anomalies, summarized in the paper by *Garcia et al.* [1987], starts with a reservoir of nitric oxide in the winter polar cap or vortex. That would be created by the dissociation of molecular nitrogen at auroral latitudes by electron bombardment, then followed by the association of N and O atoms to form the NO molecule. The atmospheric circulation in vertical-meridional planes would carry the NO so created from auroral altitudes at around 120 km toward the pole and then downward into the D region (70–90 km), then equatorward and upward again.

In the dark polar atmosphere, the production of NO would continue during auroral activity, and the concentration would build up because of its long photochemical lifetime, forming a reservoir which would remain intact until emptied by brief changes in atmospheric circulation or the end of winter. However, there would also be equatorward leakage of NO because of the atmospheric circulation, bringing some NO to lower latitudes. The latter is thought to be responsible for the smooth winter anomaly, solar UV ionizing NO molecules that move equatorward in the winter, the additional free electrons being responsible for the smooth increase in ionospheric absorption observed at mid-latitudes.

The reality of storage of atmospheric constituents in the polar vortex may be found in observations of the storage of radioactive debris from atmospheric nuclear tests at high latitudes. Thus, from early August to late December of 1962, the USSR undertook a series of atmospheric nuclear tests at high latitudes. High altitude observations [*Barcus*, 1965] of the radioactive debris from those tests showed it to be fairly uniformly distributed in longitude throughout the polar vortex in March, 1963, and then, with breakup of the vortex in April, 1963, radioactive fallout in rainfall was found at all latitudes in the northern hemisphere.

Earlier work shows that the smooth winter anomaly is positively correlated with solar and geomagnetic activity and studies (see *Davies* [1965]) indicate that ionospheric absorption is about 1.5 times normal for winter months (December–January or June–July) around the solstices and is somewhat lower, 1.2 times normal, in the months (November and February or May and August) before and after the solstices.

The stratwarm condition announced on WWV broadcasts involves a warming in the high-latitude regions of the winter hemisphere and leads to distortions of circulation in the winter atmosphere. While not mentioning stratwarm per se, *Garcia et al.* [1987] point to transport of NO out of the polar reservoir resulting from changes in horizontal atmospheric circulation; that would transport the NO-rich air to mid-latitudes where it could be ionized during the sunlit hours.

On that basis, the sporadic increases in absorption at mid-latitudes, several days in duration, are presently understood. However, the calculated effects after 20 days of auroral bombardment at an intensity level appropriate to solar maximum are the order of 18 dB absorption on 2.6 MHz for a solar zenith angle of 78.5° (i.e., $\cos(Z) = 0.2$) at 50° geographic latitude; that would amount to about 0.6 dB or less on 14 MHz or above. Moreover, *Garcia et al.* [1987] indicate that the increase in absorption would be found only in a limited range of longitudes.

This model for the sporadic increases in absorption requires two things: a prolonged production and storage of NO in the dark, winter atmosphere as well as the equatorward transport of NO by large-scale disturbances in the horizontal circulation of the atmosphere. However, a sudden warming is not required. Instead, any wave-like disturbance in circulation on the lower boundary of the polar vortex can distort it, bringing NO to lower latitudes. In the model calculations, the anomalous D region absorption at a location equatorward of the vortex rises and falls over a two-week period as the so-called planetary wave disturbance continues its development, either as a standing wave or travelling wave, at the lower boundary of the polar vortex.

How would those ideas relate to the present study, say in season or in time? First, as seen in Figure 2, magnetic and the consequent auroral activity in the first half of the study were quite strong, especially during June and July of '91, the winter months in the southern hemisphere. That would probably build a sizable reservoir of NO in the southern polar cap. In the second half of the study, the level of magnetic activity was lower and would imply less of a build-up of NO, now in the northern polar cap.

The two polar caps differ in the stability of their winter circulation, the southern polar vortex being more stable in time and only breaking up at the end of the winter season (G. C. Reid, private communication). This stability is due to the unique topography of the region, the large antarctic continent surrounded by its ocean. The northern polar vortex is less stable in time because of the more varied topography in the region, undergoing brief perturbations in circulation in the course of a winter until the final breakup at the onset of spring. Thus, with sufficient NO formed by aurora, there might be sporadic increases in D region absorption during a northern winter, but only a large one at the end of winter in the southern hemisphere.

In contrast to the northern hemisphere where the stratwarm data broadcast by WWV are presently obtained from meteorological observations in the European and Russian arctic regions, similar data are not available from the antarctic region. Thus, for the present LP study, it is impossible to speak of stratwarm conditions in the southern hemisphere or whether sporadic absorption might have been in effect during the 1991 winter in the southern hemisphere.

However, since anomalous absorption has been observed at latitudes of 40° to 70° in the northern hemi-

sphere during winter, it would seem possible to look for its effects and association with stratwarm alerts by using the long-path contacts to Europe in the second half of the present study. In that connection, during the four months centered on the winter solstice of 1991, a total of 569 ELP contacts or 5.0 contacts per active day were made with stations from Italy (40° N) to Norway (70° N), an average latitude of about 50° N.

In that same period there were 9 days of magnetic storming (*Ap* greater than 50) and 18 days of minor storm conditions (*Ap* between 31 and 50), all before the winter solstice. The first stratwarm message of '92 was issued by NOAA on January 7, and a total of 22 alerts were broadcast by January 30. In that short period a total of 147 contacts were made with stations from Italy northward, a daily average of 6.4 LP contacts per day, and the only significant drop in the daily contact rate was a brief one around January 11–12 when magnetically active conditions were attributed to a favorably positioned coronal hole on the solar disk.

While the LP contact rate showed no negative effects that were in time-coincidence or association with the announcements of stratospheric warmings, one can go further and see if that is still consistent with the theoretical model outlined above. The answer is an unequivocal "Yes" as the sun over Europe was at zenith angles well beyond 78.5° at times during January when the LP contacts were made. This can be seen by making solar zenith angle calculations for locations across Europe at those times. Another approach is by using the time of peak LP contact rate in Figure 1 in conjunction with a solar zenith angle overlay for January, showing the zenith angle as a function of geographic latitude and local time, and a world map with the same projection [*Ostrow*, 1962].

When either of those procedures are carried out it is evident that, even if NO molecules were introduced in the *D* region over Europe at those times, the LP contacts were made at times before the sun had risen high enough to ionize a significant fraction of the NO and give rise to any adverse effects due to additional ionospheric absorption.

All in all, long-path propagation seems immune to the effects of the smooth or sporadic winter anomaly as the solar zenith angles at the dusk end of the paths are too great to find any significant increases in absorption. As a matter of fact, the frequencies on the upper bands are just too high to have propagation affected by the above mechanism, and LP is sheltered even more by being a dawn-dusk affair. Thus cries of "Stratwarm" should be of no concern to DXers who operate on frequencies of 14 MHz and beyond, whether on short- or long-path. And given the fact that low-band DXers always operate in the dark of night, one should be able to dismiss the stratwarm question once and for all.

4.2 Concerning Long-Path Contacts from This QTH

Before getting to the matter of specific solar and terrestrial events and their "signatures" or effects on LP propagation, we should pause and take stock of the LP situation as it applies to this QTH. As indicated earlier, the paths to the south all pass through the antipodal point, close to Crozet Island. Some paths go through auroral latitudes in Antarctica and others pass across the geomagnetic polar plateau. But, in a sense, it is fortunate that the paths reach out in that manner; in essence, they can be related to the main issues of long-path propagation in consecutive order: antipodal focusing, chordal hops, and the equatorial anomaly.

This effort, being a "study," centers on certain variables: LP contacts made at various dates and times as well as solar and geomagnetic conditions. No issue has been made of signal strength reports, at least from the DX end of the contacts, as they are typically subjective at best, and, by involving a multiplicity of operators, are inconsistent at worst. For example, within 10 minutes on one morning, I received two RST reports from Capetown, South Africa, which differed by 4 S-units! So we'll leave RST reports alone, at least from the far ends of the LP connections.

But, at this end of the paths, some remarks about signal strength can be added to the record of dates, times, and *Ap* values. For example, I can say that the peak signal level of FT4WC on Crozet Island was typically RST 579, not bad for a 100-watt transmitter and a dipole antenna half-way around the world. But there were a few occasions when Jean's signals were S-9 on the S-meter of my Corsair. So how do I reconcile those observations, frequent and infrequent, with the idea of antipodal focusing? That is a hard question. I am still impressed with his signals but really have no way of resolving the matter, certainly no "signature" that would suggest that any strong antipodal focusing is in effect at one time and not at another.

Moving along the path toward South Africa, I can say that I have heard my share of strong signals from there too. The 100-watt signals of Al, ZS1AAX, are a case in point. They are truly outstanding, most often

peaking at RST 589, but going beyond RST 599 on occasions. With other ZS1's to compare with, I have to think that Al's antenna system, a 2-element Yagi, is particularly efficient and well placed for LP operations in this direction.

Going northward in South Africa, the signals of Stan, ZS5ADV, are a case in point also. He radiates 100 watts from a G5RV, and his signals peak at RST 579 on a fairly regular basis and even RST 599 on rare occasions. The distances to Capetown and Durban are not all that different so what can one say here? At best, it would seem to be that signals going both ways, mine and theirs, may get the occasional benefit of antipodal focusing, say above and beyond what benefits there are from having signals going mostly over salt water.

But if one looks at the ionospheric maps along those paths, there are no unique ionospheric gradients or features, even the equatorial anomaly, that would support the idea of a chordal hop along any path from here to South Africa. In short, it would appear that salt water and antipodal focusing, to whatever degree present, are the only things going for auroral zone paths from this QTH into South Africa.

The other two auroral zone paths in Table 2, to Colombo, Sri Lanka, and Bangalore, India, are at greater distances than those to South Africa, about 27,000 km as compared to 23,000 km. During quiet conditions, two stations out there, 4S7WP and VU2NI, have consistently good signals, peaking at RST 569 most of the time and coming up to RST 579 on rare occasions. In a rough sort of way, that would seem to be consistent with being at a greater distance from this QTH than South Africa.

As for any unique ionospheric structures along the paths in those directions, it must be said that there is a possibility as both are located within a few degrees of the geomagnetic dip equator. Going to the ionospheric map in Figure 19 for the time around 1200 UTC, when contacts were most frequently made with 4S7's and VU's, the great-circle paths in those directions do not show any gradients that might influence propagation until around Madagascar; from there northward, the southern part of the equatorial anomaly is present but varies as the seasons change. In that regard, the iso-frequency contours of the anomaly south of the equator are more closely spaced in June than in December, as shown in Figures 19 and 20.

Since the spring/summer season is more favorable for contacts with 4S7's and VU's because of *D* region considerations, the electron density gradient associated with the lower part of the anomaly could affect LP propagation. But it is only one-half of the equatorial anomaly and thus would not provide any gain in signal strength for the lack of a ground reflection as in a chordal hop.

Then we come to the polar paths with the termini in Table 3, and again, since they are located well south of the equatorial anomaly and the geomagnetic dip equator, there are no unique ionospheric gradients or features which would affect propagation in their direction, no matter what the time of year. And when it comes to signal strengths from locations in that group, two stand out, Z21FN in Zimbabwe and 3B8CF on Mauritius Island, and both are on a par with ZS5ADV, at least in my experience.

With that discussion completed, frequent contacts with stations north of the equatorial anomaly are next in order. These are stations in the extreme long-path (ELP) category, and in the spring/summer season are located east and west of the Black Sea and northward to Kiev, Kharkov, and beyond. They seem to be located in just the region which would be favored by signals going through the equatorial anomaly, getting the benefit of the long chordal hop, perhaps 8,000 km, and the focusing gain associated with that particular type of ionospheric gradient.

While the signals from that region are outstanding, especially considering that they come from about three-fourths the way around the earth, I admit that I am fully aware that the antenna systems (!) and power levels (!!!) used in that region are quite different from those on the African continent. And the demographics differ too, many more operators in Europe than in all of Africa and the Indian Ocean area. Of course, the troubling factor in trying to use the equatorial anomaly to account for all the frequent contacts with operators in that region is that there is no large amateur population just to the south, say in Turkey, Syria, Iraq, and Iran.

Be that as it may, one cannot operate on LP from the west coast of the USA without being impressed with the ease of contacting stations around the Black Sea and beyond during the spring/summer season. With the change to the fall/winter season, that's all there is to contact on the 20-meter band. In the absence of any physical argument to the contrary, the properties of the equatorial anomaly would seem to be the factor that makes it possible. Of course, one might think of a test that supports a contrary view and wait to see if it is ever fulfilled. For example, it would be interesting to compare LP signals received simultaneously from Cyprus or Crete and from the Ukraine. The former would not have the full benefit of the anomaly,

and, if everything else were equal, one might gain some understanding about the matter.

There are similar situations that I have come across, but only with respect to chordal hops, not the anomaly itself. For example, on more than one occasion I have heard both sides of a QSO between a ZS and a VK, and then I went on to contact the ZS. Now there are some who would argue that chordal hops occur just in the nighttime side of the earth. If that were the case, just where were the chordal hops on those occasions: between the ZS and the VK, between the VK and this QTH, or between the ZS and this QTH (with some conventional earth-ionosphere hops between the ZS and VK to account for that contact)? Given that there were no special features on the ionospheric maps for the times of such contacts, the simplest interpretation is that the basic earth-ionosphere hops were primarily responsible for the all those contacts, but perhaps with some antipodal focusing included to account for the ZS' signal strength.

But, returning to the ELP connections from this QTH to Europe, the discussion given above was *static* in the sense that geomagnetic variations were not been drawn into the matter. So one can try a *dynamic* approach, looking at how paths which terminate on either side of the equatorial anomaly fare during geomagnetic activity. An attempt made was along that line, but no significant difference was evident in the data.

Everything considered, the observations from the present study are consistent with a number of factors, none of which are new but need repeating and some elaboration. First, signal strength considerations continue to suggest that there is some sort of antipodal focusing in effect in long-path connections. The concerns mentioned by Davies may be valid on a larger scale, but focusing probably exists in smaller, stable portions of the ionosphere which have been in darkness for some time. An example would be on those paths which went west from this QTH toward Africa and Europe, into the dark, decaying region in the early morning hours. If one had to characterize the region where focusing occurs, it would seem to be in the form of a meridional segment and shaped like an N-S orange peel, similar to radar antennas which scan in elevation.

In contrast to that example would be paths which went from this QTH toward the east, to Sri Lanka and India. Signal strengths from those directions never came up to the level of those from southern Africa, and one cannot argue for any sort of focusing gain to explain the observations. And if one looks at the matter in detail using The DX Edge, it is apparent that portions of those paths were well illuminated just before the terminator moved into a favorable position for long-path contacts. The changes in solar illumination would probably serve to work against the stable conditions needed for antipodal focusing, as Davies would argue.

Next, from this QTH until the equatorial anomaly is reached, signals most likely propagate only by means of earth-ionosphere hops, say six or seven hops of about 3,500 km. That conclusion stems from the lack of ionospheric structures in the early parts of a long-path that are comparable in size, electron density, or spatial variation to those within the equatorial anomaly.

While chordal hops are attractive in aiding discussions of propagation over great distances, if one is going to invoke them a suitable set of ionospheric gradients must be identified to support the proposal. While the gradients around dawn and dusk are regular parts of the ionosphere, they do not come up to the degree or extent of the equatorial anomaly, already a proven part of trans-equatorial propagation on short paths from one hemisphere to another.

4.3 Concluding Remarks

In discussing any matter of technical or scientific interest, one must always touch base with those who have gone before, making reference to their work lest one be accused of not giving them their due or, even worse yet, the cardinal sin of "re-inventing the wheel." So let me say right here and now that long-path propagation had its foundations in the early work on around-the-world echoes. As best I can tell that dates back to the work of Quaeck and Moegel (Germany) in 1926, as cited in the article by Hess [1948].

The article by Hess has interest of its own, dealing with research on short- and long-path signals, so-called "direct signals" and "indirect signals," done from 1941 to 1945 by the Institute of Physics in Berlin-Gatow, Germany. It shows some oscillograph recordings of SP and LP signals as well as RTW echoes, even one HF signal which went three times around the earth. And the article touches on the diurnal variation of "echo activity," showing something of the daily and seasonal variations for signals from the USA. And, while details were lacking, brief mention is made of the fact that echo signals were disrupted by ionospheric disturbances due to auroral activity and magnetic storms.

In the amateur radio literature, long-path propagation and gray-line openings seem to be synonymous.

Thus there is the article by *Hoppe et al.* [1975] about gray-line DXing. For those with an inclination toward historical matters, it is of interest to note that gray-line considerations were discussed in the article by Hess, dealing with the RTW echoes recorded in the 1941–1945 period. The language was a bit different, the "globe-girdling twilight zone," but the idea was the same: echo signals propagating best along the great-circle which has the same direction as the twilight zone or gray line.

And, finally, in the article by Hess there is even mention of a theoretical scheme proposed by Von Schmidt in 1936 that contains the idea of propagation without intermediate ground reflections, somewhat like chordal hops. But the origin of that theory was founded more in the near-constant timing or delays of echo signals than their signal strength, and it lacked any sort of ionospheric foundation. Given that, it may have been a case of "the right answer to the wrong question!"

Now, having paid homage to the ancients, let's turn to the present, reiterating some features from earlier work and adding others from the present effort. Thus, as noted at the outset, the present study shows that long-path propagation is an integral part of HF propagation during undisturbed conditions. Except for major storm conditions when both short- and long-path propagation are severely disrupted, it is something that can be expected on a regular basis, not a brief, fleeting condition that comes and goes. And when present, long-path propagation provides a means of communication over a wide range of distances, latitudes, and longitudes simultaneously . Thus, in the present study, it was not uncommon to hear LP signals from as close as Crozet Island and Africa or as far as Europe at about the same time.

But the mode of propagation of LP signals on a path is a difficult matter; it is not clear whether it involves only a multi-hop mode in the conventional sense, or whether it also includes significant ionospheric focusing as well as chordal hops. And, in trying to predict LP openings, the former point bears not only on calculations of signal strength but also the predictions of the maximum usable frequency on the path. On both points it is worthwhile to digress for a moment and discuss how the technique developed in the course of time and how these matters are handled now.

Predictions of the maximum usable frequency on paths were first made before WW-II by the group in the National Bureau of Standards (NBS) under the leadership of Newbern Smith. The technique was to use the critical frequency at vertical incidence for the mid-point of a single hop to determine the critical frequency at oblique incidence. That technique was limited to distances of about 3,000–3,500 km.

During WW-II the technique was extended to greater distances, two or more hops, by the control-point method developed at NBS and independently by K. W. Tremellen in the U.K. In that method, the success or failure of HF propagation was considered to be controlled largely by conditions near the ends of a path. Thus the two critical frequencies for oblique incidence are calculated for points about 1,500–2,000 km from the ends of the two termini, and the lower of the two is taken as the maximum usable frequency (MUF) of the path. If the operating frequency were below that value, the path should be open. Of course, the possible screening by the E layer has to be considered as well in determining the MUF value at any given time.

The next improvement was to add signal strength calculations based on some scheme for determining the ionospheric modes involved. Thus, among the programs available to amateur radio operators, the IONPRED program due to Raymond Fricker uses the MAXIMUF algorithm to test for conditions appropriate to refraction at F layer heights along the path and determines the simplest mode, including the possible effects of the E layer, available between the transmitter and the receiver. The same approach is used in the MINIFTZ4 program, but, instead of using mathematical functions, the critical frequencies at points along the path are obtained by interpolation from a large database in geographic coordinates. Finally, the recent versions of MINIPROP [*Shallon*, 1988] take a somewhat different approach, testing for the various E and F modes that are possible at a given time, and then searching for the one which produces the strongest signal level.

Those techniques for short-path propagation have been taken over in making MUF and signal strength predictions for long-path propagation. They are reasonably successful in predicting MUF's for LP openings, especially when one considers the great length of the paths. Given the dawn-dusk nature of the paths and the results shown in Figures 23 and 24, one would expect that the agreement would be best when the morning terminus is in the winter hemisphere. The reason for that choice is the morning portions of the path have been in darkness the longest and the critical frequencies near that end would increase from their lowest values as the sun rises. In contrast to that, portions of the path farther along have been in sunlight for hours and F region ionization decays slowly with sunset. Under those circumstances, the dawn portion is the one which determines when the MUF exceeds the operating frequency and the path opens.

In contrast to MUF calculations, which depend on features of the ionosphere at high altitudes, signal strength calculations involve not only signal spreading but ground losses with reflections along the darkened path and D region absorption on the sunlit ends of the path. But the problem with LP calculations is that the hop structure is really unknown, say where and if chordal hops are present, reducing signal losses on the paths. Thus, lacking theoretical guidance, the calculations are done on a multi-hop basis and generally yield signal strengths which are too low.

So actual LP propagation defies the conventional ideas of signal loss calculations that are used in short-path propagation, the signals being just too strong for the great distances involved. If one approaches the question in steps, as with the various paths from this QTH, the first thing to consider is antipodal focusing, as suggested by *Hortenbach and Rogler* [1979]. As noted earlier, Davies argues against the importance of that type of focusing because of the great geographical variations of ionospheric conditions. To that, one could mount a counter-argument if it were possible to find times or paths where the geographical variations were small. If that were the case, then one could suggest that some focusing, with the corresponding enhancement of signal strength, might be possible.

Thus, in using HF propagation computer programs for the shorter of the long-path circuits, one might add to the calculated signal strength something like 5–10 dB for antipodal focusing. After that, the question is what to do if a path also goes across the equatorial anomaly. If that were the case, some additional correction would be required for the signal strength. Of course, both of those factors are in addition to any increase in signal strength due to the gain of antennas that are more complicated than dipoles or power levels in excess of 100 watts output, the usual assumptions in propagation programs.

If such empirical adjustments give reasonable results for paths from one QTH, then the computer programs may be used for other locations to examine their possibilities of LP DXing. It then is just a matter of looking into dawn-dusk paths for the various times of the year. After that, one gets into demographic factors and other matters which bear on DXing. These have all been discussed earlier in this article and should suffice. So, after planning one's LP strategy and finding a time that is magnetically quiet, these ideas can be put to the test. If you haven't tried LP before, you will be pleasantly surprised at what you can accomplish.

4.4 Quantitative Summary of the Long-Path Study

In summarizing the results of this study, I will deal first with the observational material, then the solar and terrestrial conditions. So first we turn to LP contacts in the two seasons.

In the summer/spring season, there were 669 LP contacts in the log. Given the number of active days, that corresponded to an average of 4.0 LP contacts/day. And the contacts in that season reached from Crozet Island (20,465 km) to Enköpping, Sweden (32,558 km).

Typically, in the spring/summer season, the LP opening began around 1200 UTC, signals from FT4WC and UJ8JI generally starting the session. And the sessions closed around 1500 UTC, contacts with Africa and Europe being the last in the log for the day. If the spring/summer LP sessions were to be characterized in more detail, it would be that each session involved a series of individual, but over-lapping, openings: first, to the antipodal region as well as east to Sri Lanka and India, then stations from Malawi, Mauritius, Reunion Island, and Mayotte Island in the Indian Ocean, followed by stations with prefixes from southern Africa. say ZS, ZE and 9J2, and finally contacts with UB5's in the Black Sea area and beyond into Europe.

But sunlight on the extreme long-paths varied considerably where they terminated in the summer hemisphere. Thus, as mid-summer approached, the number of ELP contacts per week decreased significantly because of D region absorption, and then after mid-summer they increased again. It should be noted that there was some magnetic storming in this period, during weeks 8, 11, 16, and 21. But the trend was there, a slowing of the ELP QSO rate during the peak summer season followed by a steep rise as solar illumination on the paths decreased with the approach of the fall/winter season.

The spring/summer season involved comparable numbers of contacts on auroral zone paths and extreme polar paths. If one removes the contacts with India and Sri Lanka from the auroral zone part of the database, it is possible to set up a comparison of the effects of magnetic activity, as given by the Ap index, on paths which terminate in southern Africa, on the one hand, and others which continue across the equatorial anomaly into Europe, on the other.

While the details will not be given here, it did not prove possible to find any significant difference in the response of the two paths to increases in magnetic activity. On that basis one must conclude that the

determining factor for the success or failure of LP propagation is in the area that the two paths had in common, the auroral zone. Put another way, there is no evidence that magnetic activity had any effect on the equatorial anomaly without also affecting ionospheric conditions in the auroral zone.

But if one compares propagation on auroral and sub-auroral paths, there is a difference in their response to magnetic activity. While this result was not derived directly from the present observations, the log data collected from operators at lower latitudes for the same time period show the effect, propagation on sub-auroral paths holding up better than on auroral zone paths in the face of magnetic storm conditions. This is to be understood in terms of lower latitude paths being more sheltered from disturbances starting on the boundary of the magnetosphere. Thus the extreme portions of the lower latitude paths are on the feet of magnetic field lines which extend out 2–3 earth radii while those on auroral zone paths go out 6–7 earth radii. But in the face of extreme storm conditions, *Ap* well over 100, all paths are disrupted and propagation fails.

In the fall/winter season there were 1011 LP contacts in the log, ranging again from Crozet Island and now to Vadsö, Norway (33,368 km). But the openings were much shorter, starting in the hour before local sunrise and lasting about 90 minutes or so. The stations in the Indian Ocean area, from 4S7 and VU to 3B8 and FR5, gradually disappeared from the bands due to their paths going through regions in the southern hemisphere which were increasingly illuminated.

While ionospheric absorption had an adverse effect on those signals, its effect was just the opposite on the extreme long-path signals to and from Europe. Thus, with increasing darkness in the northern hemisphere, there was less ionospheric absorption at the far end of the paths and contacts with Europe became more numerous.

But that had its bad side as well; short-path signals from Europe started coming through earlier in the day than in the spring/summer season. Thus it required constant vigilance to avoid pursuing a contact with an SP signal coming in the back lobe of the beam, mistaken for an LP signal. And with the high power levels run in Europe, to say nothing of their larger antenna structures, it became a significant problem and took a lot of time out of the shorter LP sessions in fall/winter. But in spite of that, the contact rate was higher than in the spring/summer season, averaging about 5.0 contacts per LP session.

If one were to make a value judgment about which of the two seasons was the most rewarding, it would depend on the personal point of interest. Thus, in terms of variety of DX signals heard during LP sessions, the spring/summer season would be the best, by far, when it comes to working "New Ones." This is simply due to the fact that the Indian Ocean and east African stations would be available then and, curiously enough, the fact that it would be the cooler season on the African continent.

In our fall/winter season the opposite is the case, and it was not uncommon to hear complaints from African stations about warm temperatures (about 30° C) in the radio shacks over there. In addition, with the shift of the LP opening to later times, it came into conflict with their dinner hour! But those complaints were minor; the real problem was with the thunderstorm activity that develops during their summer.

While this was alluded to in personal correspondence, a search of the literature revealed the magnitude of the problem. Thus *Campen et al.* [1960] provide information on the frequency of occurrence of thunderstorms over the entire globe, month by month. Starting in September thunderstorm activity in Africa spreads eastward from central Africa into the southern end of the continent. By January it fully engulfs the southern part of Africa and Madagascar, showing the highest rate of thunderstorm activity (more than 25 days per month) on the entire earth, peaking in the area around Madagascar as well as Zimbabwe and Malawi. Then, as summer turns to fall, the thunderstorm activity retreats northward toward equatorial latitudes. So little wonder that African stations are not found on LP at those times. It's more of a matter of self-preservation than anything else.

If one enjoys the idea of working stations at great distances, say three-quarters the way around the world, then the fall/winter season comes in first as the most rewarding experience. I wouldn't think that one could work WAC on LP with any ease, but if you're an oblast hunter you should be able to earn an LP endorsement for the R-100-O Award by contacting 100 Russian oblasts using the "back door." Thus, just in this year, I've managed to work more than 70 oblasts via LP. More specifically, I've contacted about a dozen oblasts with the UB prefix, and then UA9, UA3, UA4, and UA6 in a descending order, followed by Byelorussia, the Baltics, and the lower part of the USSR from Azerbaijan (UD) to Tadzhikistan (UL). By the looks of it, however, it will be a while before that region of the world stabilizes to the extent that one can look forward to a new set of DX awards.

Turning to the geophysical conditions during the study, it is fair to say that it was one mainly of magnetic disturbance. This is shown by the data in Figure 16. Beyond that, NOAA's *Monthly Activity Summary and Solar Cycle Outlook* released in September '91 pointed out that since late March '91 there had been a near-record number of days of major geomagnetic storm levels or above. Indeed, there had not been such a high level of activity since '60. Thus, while geomagnetic coordinates and disturbance are relevant to any discussion of LP propagation, the high level of magnetic activity during the study made them all the more important.

The other potential source of disturbance for long-path propagation, polar cap absorption events, never really played a significant role in the study. As may seen from Figure 3, solar proton events were most numerous and intense during the spring/summer part of the study. But PCA effects are the strongest in the sunlit polar cap, and that was the northern one during the spring/summer season, a hemisphere away from all the paths in this study.

Now PCA effects are most evident on polar paths when they occur in the absence of any geomagnetic activity. But, again, Figure 2 shows that magnetic activity was most frequent and intense during the spring/summer season. The one isolated PCA event that occurred when the southern hemisphere was in sunlight was on February 7, 1992. That event had a peak proton flux of 78 pfu and a maximum absorption of 1.5 dB on 30 MHz at the Amundsen-Scott Base (75° S mag lat) in Antarctica (T. J. Rosenberg, private communication).

In comparison to the solar proton event of June 11, 1991, cited earlier, with a proton flux of 3,000 pfu and giving 17 dB absorption on 30 MHz with vertical incidence, the February event was puny. However, at the peak of that event, late on February 7, it was capable of producing about 9 dB of absorption for 30 MHz signals at oblique reflection on the polar cap. Earlier on that day, however, long-path propagation to Europe on 14 MHz was normal, seven contacts reaching from the Black Sea to as far north as Norway. However, the next two days were completely disrupted by magnetic storm conditions with *Ap* in excess of 50, making it impossible to observe any effects due to solar proton bombardment of the southern polar cap. After that date no other significant PCA event presented itself for study on LP.

I would be less than honest if I didn't say that I was secretly hoping for a big PCA event, one that might come out of geomagnetic quiet during the height of summer in Antarctica. That would have done no particular harm as most of the DX contacts on LP then were into Europe, predominantly countries which do not rate high on the "Ten Most-Wanted DXCC List." But it would have been most interesting to follow with LP propagation.

Unfortunately, the antarctic continent is not particularly well instrumented these days for HF propagation studies. Thus the only installation that I know of is at the Amundsen-Scott Base. That would give a limited view of the time-variations of ionospheric absorption due to the influx of solar protons, just from one location. However, the Antarctic Division of the National Science Foundation has plans to install a network of unmanned instruments in the coming years, so we will just have to be patient and wait for those instruments to be in place. Then, LP DXers can watch propagation and the NOAA/SESC BBS for news of a big PCA event. With that, we can get down to the business of comparing experiences on the different paths across the southern polar cap. It will certainly be interesting, I'm sure, and add more to the lore and understanding of LP propagation.

In the last analysis, the study provided data on the effects of seasonal factors, examples of sporadic disruption due to magnetic storms, and quantitative results on the negative correlation between magnetic activity and long-path propagation. While those results might have been anticipated at the outset, one could not foresee the magnitudes involved. That being the case, if one is interested in the quantitative side of HF propagation there is little choice but to carry out the observations.

4.5 Long-Path Propagation in a Nutshell

If you're the kind of person who immediately goes to the last chapter of a detective story to find out "whodunit," you've come to the right place. Thus, in what follows, I will give a qualitative summary of LP propagation as I know it and how it applies to that greatest of all pursuits, LP DXing.

First, the serious DXer knows that LP is a dawn-dusk affair, one that is essentially controlled by ionospheric absorption in the *D* region. Thus the times of any LP opening or closing are set by solar illumination on the extreme ends of the path. More specifically, competing factors are 1) sunrise on the *F* region in the

winter hemisphere which raises the MUF and opens the path and 2) signal absorption in the *D* region on the morning portion which grows at a faster rate than the absorption decreases on the dusk end, ultimately closing the path.

Beyond that, actual local times for incoming signals are determined essentially by one's antenna set-up — height above ground, gain, and exposure to local QRN. Just when contacts can be made depends, of course, on one's transmitter power and receiving conditions at the other end of the path. Power considerations are particularly important near the end of an opening, the path staying open longer for QRO signals.

Any sort of geomagnetic activity which decreases the ionization in the *F* region at refraction points along the path can only shorten the duration of the opening or close it all together. The same is true of any solar event which increases the ionization in the *D* region, say a sudden burst of solar X rays (SID) or the arrival of solar protons in the polar cap, a PCA event. But, during quiet conditions, the local times of LP openings will shift with the seasons, being earliest near the summer solstice and latest around the winter solstice, starting about 2–3 hours later for a path which is open year-round, as is the case from the West Coast to Europe.

LP openings vary in duration, from about 3–4 hours in the spring/summer season to 1–2 hours in the fall/winter season. During the spring/summer season, a dawn opening is really a series of shorter openings which overlap in time. Here on the West Coast it starts with signals from 80° east longitude, say UJ8's, VU2's or 4S7's, and then steadily moves westward with the sun toward stations in central Europe, say UB5's, YU's or LZ's. With that variety of locations, some paths from the West Coast go off to the east of south and toward the sunlit hemisphere but are protected by the winter darkness in the southern hemisphere. The other paths toward Europe go off to the west of south into the dark hemisphere and thus depend on the level of solar activity for critical frequencies to support propagation on them.

During the fall/winter season, the more easterly stations are just not heard on LP as their signals have been wiped out by solar illumination on the portions of the paths in the southern hemisphere. And the other paths that went westward across a darkened ionosphere in the spring/summer season now come close to fitting the conditions for gray line propagation. As a result, the majority of LP contacts during this period are with Europe, opening with UB5's and HA's and then finally closing with F's, G's, and LA's in northern Europe.

From the standpoint of propagation, however, contacts with the southern portions of Africa are still possible but simply few in number. This is due to the fact that intense afternoon thunderstorm activity shifts from the equatorial regions of Africa into the southern and eastern portions of the continent with the coming of their summer.

A viable LP circuit depends on having a significant amateur population at the ends of the path. However, the ease of LP communication depends on the QRM and QRN that the operators experience. Given the dawn-dusk nature of LP connections, the operators in the dawn sector have the least local interference to contend with, and the operators in the evening sector have the most due to the increase in human activity after daylight. Of course, there is always the possibility of QRM from signals on paths along the great-circle route which happen to be open at the time.

The results of the present study are expressed from the dawn-to-dusk perspective, appropriate for early morning LP operations from the west coast of the USA. However, one could operate the other way around, making dusk-to-dawn LP contacts. The general ideas expressed here would still apply, one only needing to change the seasons by six months and the time of day from dawn to dusk. That is because of the spatial symmetry of the terminator and the role of ionospheric absorption in the lower ionosphere.

It should be noted, however, that the *F* region is not symmetrical in that respect because the sun goes from east to west across the sky, the slower rate of electron-ion recombination at the higher altitudes in the *F* region, and the drift of ionization in the geomagnetic field at equatorial latitudes. Thus, while the landmarks along a great-circle route would remain the same, the ionospheric structures would be encountered in reverse order in dusk-to-dawn contacts.

As a result, dusk operations from the West Coast mean that the evening portion of the equatorial anomaly would be encountered first, out in the Pacific Ocean instead over north Africa. That would make possible fall/winter LP contacts with Sri Lanka and India where they are excluded because of their paths being sunlit for dawn-to-dusk operations. And dusk-to-dawn paths to Africa and Europe would be excluded in the fall/winter season because the entire south Pacific Ocean is sunlit during those hours.

For LP DXing from other locations, say the East Coast or elsewhere, the possibilities and problems are

best examined using a propagation program such as the new MINIPROP PLUS [*Shallon*, 1988]. Of course, one can cite possibilities, say the East Coast to Australia and Japan, as noted in ARRL publications, but those are only individual cases and somewhat limited when it comes to variety of DX. More general cases, offering greater opportunities, are from Australia to Europe or Indonesia to South America.

In any event, whatever the path, the experience from month 55 to month 67 in Solar Cycle 22 indicates that LP contacts can be made year-around on 14 MHz, the only exception being days during major magnetic storms. Thus there will be days when the LP signal strengths are amazing and other days when LP signals, or *any* signals for that matter, are not heard.

Between those two extremes of LP propagation, there is a moderate negative correlation (−0.43) with magnetic activity, at least on paths which go through the auroral zone. Thus, when the Ap index rises, LP signals are weaker and less numerous with the result that the number of contacts one can make in a day will decrease. But some LP will still be open: you just have to work harder at it.

And those problems result from changes of ionization in the auroral and polar F regions when solar wind plasma impinges on the outer boundary of the earth's magnetic field. On paths which only reach sub-auroral latitudes, say from southern California to South Africa, a separate analysis of LP contacts during the recent spring/summer season indicates that those paths are more successful for LP propagation than the other paths which go more poleward, as is the case for the Northwest.

There are seasonal factors in LP DXing, and here on the West Coast the greatest variety in DX prefixes are found at distances of 24,000 km during the spring/summer season while distances up to 32,000 km are reached during the fall/winter season. Again, these differences result largely from seasonal changes in D region absorption on the paths.

Given that the spring/summer season is the most rewarding when it comes to working "New Ones," any operation on LP in the fall/winter season is like weight-training, keeping you in shape for the upcoming DX season. And a bit of practice busting through pile-ups wouldn't hurt either.

At this point in Cycle 22, the sunspot number is high enough that MUF considerations are important only on the higher bands, say 21 and 28 MHz. That situation will gradually change as we go farther toward the solar minimum, LP contacts on 14 MHz becoming more spotty in time and LP DXing slowly shifting to 7 MHz. In that regard, 7 MHz LP DXing is already a "winter sport" with its own loyal following, but, because of the lower frequency, it is only available from QTH's where the DX paths stay within darkness in the southern hemisphere.

The mention of paths and their relation to darkness brings up another important point in LP DXing: one really needs a good atlas, The DX Edge, or better yet a good propagation program like the new MINIPROP PLUS. While The DX Edge is helpful in giving rough indications of the geometry in LP propagation, a program like MINIPROP PLUS goes further and gives not only MUF information but also signal strength data and shows the geometry for both short- and long-paths in relation to the terminator.

Thus, with one's computer, it is possible to understand what is in hand at any moment as well as to plan ahead for DXpeditions off in the future. In that regard, the "back door" via LP can be quite effective in avoiding short-path QRM from stations between you and the DX in those difficult zones. In addition, those tools are essential for other operators to explore the LP possibilities from their locations, say Australia to Europe or Europe to the Orient.

As for the other tools needed to be effective in the pursuit of LP DX, at a minimum they start with a good transceiver, complete with RIT and XIT, and a beam antenna, say a 3-element Yagi which is at least a half-wavelength above ground and well removed from nearby objects. With that sort of set-up, you're in business, ready to leap out of bed when the alarm goes off and start looking for LP DX.

The LP signals you hear will have that "DX sound," but they are quite steady considering they often pass through high magnetic latitudes in the south. From time to time, however, you will hear various forms of multi-pathing. This happens most often in the fall/winter season when both short- and long-path propagation can be in effect simultaneously.

Then, if you operate from a low-noise site like mine, on an LP beam heading to the south you can hear the weak, short-path signal coming through your back lobe, followed by the delayed, long-path signal . The short-path signal is like a "leading ghost," to use TV parlance. If you turn your beam north to the short-path direction, then the long-path signal will be a "trailing ghost," coming in after the short-path signal starts.

And there are also occasions when you'll hear the more common delayed echoes from higher ionospheric modes, just like on short-path when you hear a $3F$ hop signal after one on a $2F$ mode. This happens most

often when the station at the other end is running high power (as is the case for some stations in Europe). Under such conditions it would be good to know what the F/B ratio of your beam is like and something of its horizontal pattern.

Given the power levels run by some operators at the other end of an LP connection, it's quite possible to be fooled, thinking that you hear an LP signal when actually it's a strong SP signal reduced by about 20 dB and sneaking in the back lobe of your beam. Of course, the bigger the beam, the better, as the F/B ratio is greater and the gain as well.

Finally, we come to the marvel of the strength of LP signals, from more than half the way around the world. When you hear them, you can think of the challenge that they present to theoretical understanding. There are the ideas of focusing and chordal hops to consider, but they cannot be invoked willy-nilly as some sort of ionospheric structure must be involved, such as found with the equatorial anomaly. So ponder the signals you hear and think of how they can be explained. It's a challenge!

In a qualitative sense, I think that pretty well covers the subject, so now that you have "the answers" you can go back to the beginning of this article and see how the questions were raised. I say that in the hope that you will dig deep into what I present and come away from all this with a sounder understanding of LP propagation. While LP propagation abounds with anecdotes, the information derived from a large, continuous database provides a better and firmer foundation for your LP DXing and will last well after the echoes of the amusing LP stories have all died away. So go back to the beginning now and ponder all the figures, tables and statistics. The whole story will be there, right before your eyes.

Long-path is more than just beyond one's antipode;
it's a state of mind, a way of life.
NM7M

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